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AN AGENT-BASED DISCRETE EVENT SIMULATION APPROACH FOR MODELING LARGE-SCALE DISASTER EVACUATION NETWORK

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ABSTRACT

The need for appropriate evacuation strategies is always a daunting problem when confronted with a large-scale natural disaster. The challenge is to find a policy that maximizes the number of survivors and minimizes the total cost simultaneously under a set of resource and geographic constraints. We develop an agent-based discrete event simulation (ABDES) evacuation framework based on an embedded geographic information system (GIS) module to solve a network evacuation problem that involves multiple candidate shelters, multi-priorities evacuees and several vehicle types. The evacuation framework consists of three interacting components: a disaster scenario generator module, a GIS module for analyzing an evacuation network, and an ABDES module. We conduct experiments using the city of Galveston as an example. The evacuation framework offers insight to decision-makers about the number and location of shelters, allocation and assignment of evacuation vehicles, and distribution of relief resources that are required to complete a large-scale evacuation.

1 INTRODUCTION

The World Health Organization (WHO) (1995) defines a disaster as any occurrence that causes damage, ecological disruption, loss of human life, and deterioration of health and health services on a scale sufficient to warrant an extraordinary response from outside the affected community or area. Natural disasters such as hurricanes, earthquakes, floods, volcanic eruptions, drought, and famine have been parts of our daily lives. Such natural disasters are often large-scale, rapid-onset, and overwhelming catastrophes relative to the scale of damage and the toll of casualties. Over the past few years, the growth rate of victims affected by large-scale natural disasters (LSNDs) has decreased steadily, but the estimated damage cost has increased rapidly. According to the Centre for Research on the Epidemiology of Disasters (CRED) (2014), there was a small decrease (-11.08%) in the total number of people affected by natural disasters in 2011 compared to the annual average from 2001 to 2010. However, in 2011, the worldwide natural disaster damage (US$ 362.8 billion) increased by 272.2% compared to the annual average damage from 2001 to 2010 (US$ 97.5 billion). It is worthwhile exploring the disaster evacuation problem that can potentially offer improved medical care for affected people, which can further reduce human casualties. In this paper, we look at a simulation modeling approach on the LSND evacuation problem aimed at improving access to medical facilities for affected people.

Providing rapid medical treatment is of utmost importance in any disaster. Transporting patients to medical facilities quickly is a research problem that has been studied to some extent. In this context, the purpose of this paper is twofold. First, an agent-based discrete event simulation (ABDES) approach is addressed for determining a tactical evacuation plan for patients with different emergency care priorities and multiple types of vehicles. Second, a GIS technique is applied to the ABDES modeling for a more realistic evacuation model with update from actual traffic conditions. In fact, one of the challenges is to find a policy that can maximize the number of survivors and minimize the total evacuation cost simultaneously under a given set of resource and geographic constraints. The proposed ABDES model enables several decision-makers to effectively determine the optimal evacuation policy.

The rest of the paper is organized as follows. Section 2 reviews existing related simulation models for the evacuation network problems and discusses some advantages and disadvantages of the models. Section 3 describes the LSND evacuation network problem and a novel simulation modeling approach for the problem. Section 4 considers how simulation modeling methods and GIS techniques can be applied to the evacuation network problem simultaneously. Performance evaluation of the proposed simulation approach using computational results is summarized Section 4. Conclusions and future works are presented in Section 5.

2 LITERATURE REVIEW

Simulation modeling has been frequently used as a strategic planning tool in modeling and assessing LSND evacuation networks. The behavior features of individual evacuees (or patients) and evacuation traffic flow can be modeled effectively while using simulation in evacuation planning. There are three types of simulation models – macroscopic, microscopic, and mesoscopic models.

Macroscopic simulation models represent an evacuation traffic flow with the highest view of the transportation network modeling, where there are no detailed explanations on individual objects such as evacuees, vehicles and relief resources. Simulation-based Dynamic Traffic Assignment (DTA) models often use a macroscopic simulation to describe large-scale evacuation traffic flow. In terms of the modeling paradigm, DTA models may be typically categorized into two paradigms: analytical models and simulation-based models (Ziliaskopoulos et al. 2004). Most analytical models cannot describe the realities of traffic road networks due to the assumptions and simplifications in the model. In addition, as the size of an evacuation network problem increases, it is intractable to solve the problem using analytical DTA models. In order to overcome these limitations, simulation-based DTA models can be applied to model large-scale evacuation problems although simulation-based DTA models are often unsuccessful in ensuring optimality and convergence. Kwon and Pitt (2005) address the feasibility of applying Dynasmart-P for evaluating the plans for traffic evacuation in downtown Minneapolis, MN. Balakrishna et al. (2008) present a simulation-based framework to model an emergency traffic network in Boston, MA by using DynaMIT. Songchitruksa et al. (2012) consider the quantitative evaluation of the performance of the evacuation plan in the Houston-Galveston, TX region using DynusT. Due to the availability of state of the art computing hardware, it is possible to run large-scale evacuation network scenarios, but it is still a time-consuming effort and requires high computational cost (Xie, Lin, and Waller 2010). Hence, a microscopic simulation is often used for developing evacuation simulation models where all evacuees and vehicles are represented as individuals.

In contrast with the macroscopic simulation models, microscopic simulation models can depict various detailed activities such as individual evacuee movements, evacuation vehicles speed and routes, as well as relief resources locations. Many Cellular Automata (CA) models have been used with considerable success in emergency evacuation and are typically used in microscopic simulation models. Because evacuees and vehicles are described individually in the CA models, they can have different values or parameters such as transportation cost, care cost, and vehicle speed. Zhao et al. (2008) apply the CA model into a residence evacuation by considering human psychology and behavior characteristics. Alizadeh (2011) proposes a CA model for simulating to evacuate from rooms with obstacles. The principal distinction between CA models and other simulation models for evacuation is the discretization of space. As a result, typical CA models are not applicable to large-scale evacuation network problems. CA models need to have large cells to design a large-scale evacuation traffic network, which leads to enormous computing costs and times.

On the other hand, mesoscopic simulation models have successfully involved many individual agents such as evacuees and vehicles as well as described large-scale evacuation network problems. Chen and Zhan (2008) examine the effectiveness of concurrent and phased evacuation plans with an agent-based simulation (ABS). The traffic flows of the individual evacuation vehicles are modeled and the collective behaviors of evacuation vehicles are considered. As a result, simulation results related to the road network structures and population density are generated. Lämmel, Rieser, and Nagel (2008) consider the method to adapt a multi-agent traffic simulation into a large-scale pedestrian evacuation problem using MATSim. Lämmel, Grether, and Nagel (2009) also introduce a microscopic simulation model for large-scale pedestrian evacuations. Yin et al. (2014) present an ABS model for hurricane evacuation, which can predict comprehensive activity-travel patterns. Chan, Son, and Macal (2010) explain how to use ABS on emergent behaviors and address distinctions between the ABS model and other discrete event simulation (DES) models. ABS models is found to be an appropriate approach when there are many objects to interact each other in succession. In contrast, DES models are not suitable to model complicated interactions and behaviors of agents, but rather are modeled in terms of system states and discrete events. ABS can facilitate modeling evacuation network problem with flexibility and autonomy encapsulation while DES is capable of reducing the computing times. An integrated simulation model for large-scale evacuation network problems, where ABS and DES are combined, can provide better performance and more efficient computing environment compared with ABS models alone. By integrating DES with ABS, an ABDES framework has been employed for large-scale evacuation models (Wagner 2004; Wu et al. 2008; Chan, Son, and Macal 2010; Zhang, Chan, and Ukkusuri 2014). Wagner (2004) consider an extension and refinement of the typical DES framework by reinforcing it with the Agent-Object-Relationship (AOR) model, but the proposed simulation framework has a time-step-based scheduling concept for permitting real-time updates of each agent and its surroundings. Zhang, Chan, and Ukkusuri (2014) propose an ABDES modeling framework for large-scale evacuation that allows a hybrid simulation space and adopts a network structure to describe the interactions of distinct agents. When ABDES is applied to a large-scale evacuation network, the integration of ABD and DES makes an effective method as it takes advantage of operational flexibility and computational efficiency.

In addition, the evacuation problems are inherently spatial, but many of the present papers have been not dealt with the GIS domain so far. A GIS is a system for managing specialized geographic data, which can take data from various geographic sources, visualize the geographic information based on the coordinates, and analyze and retrieve spatial information (Na and Banerjee 2014). The simulation modeling methodologies can be used to simulate the evacuation problem, and the GIS technique can be adopted for spatial analysis and graphic processing. GIS can be a crucial tool in several disaster risk management problems. Church and Cova (2000) describe how an optimization model can be integrated within a GIS system in order to generate maps of evacuation risk or vulnerability. Wu et al. (2008) develop an integrated ABDES evacuation simulation model with GIS components and address a rule-based system that can describe the processing procedures of each emergency responder and incident commander. Horner and Downs (2010) substantiate a GIS-based spatial optimization model to investigate substitutive hurricane disaster relief distribution plans. The integrated capabilities can provide a great platform for special GIS application to disaster risk management planning.

In this paper, we develop an ABDES evacuation framework based on an embedded GIS module. Such an integrated simulation modeling approach can enable evacuation planners to evaluate several scenarios of evacuation problems. In particular, we integrate the ABS and the DES approach for extending a modeling area on the LSND evacuation network based on network analysis methods of GIS techniques, which is different from existing evacuation simulation models.

3 INTEGRATED ABDES MODELING ON LARGE-SCALE EVACUATION

In this section, a LSND evacuation problem with complicated traffic networks is described first. Next, a modeling logic is designed to explain the behaviors and movements of both evacuees and vehicles during the entire evacuation procedure. This is followed by the description of the method to combine an ABDES model and GIS techniques to include the spatial aspects of the problem in the model.

Initially, evacuees are taken to staging areas as soon as they are found, then their priorities are determined by a triage system, and emergency treatment is provided at the staging area based on their severity level. Staging areas must be spacious areas located around the disaster affected region and accessible by evacuation vehicles. Shelters are temporary medical facilities that can be used to house evacuees during the period of evacuation. There are three possible types of shelters: extensive shelters, restricted shelters, and other large shelters without medical infrastructure. Extensive shelters (e.g., hospital) are large medical facilities that have existing capabilities to provide care for the various priorities of evacuees. However, the capacity of extensive shelters in an affected region is often limited. Restricted shelters (e.g., clinic, medical center) are smaller medical facilities compared to extensive shelters, and have existing capabilities to provide treatment for evacuees. The number of restricted shelters in an affected region is expected to be higher than the number of extensive shelters, but restricted shelters are also limited. Other large shelters without medical infrastructure (e.g., sports arena, theaters, schools) are extensive facilities that can accommodate a large number of evacuees with suitable amounts of basic amenities such as climate control, bathrooms, kitchen, and sufficient space to organize beds. Such facilities do not have the inherent capabilities to take care of various priorities of evacuees. The restricted shelters and other large shelters without medical infrastructure are called candidate shelters, which can be transformed into evacuation shelters during a period of evacuation only.

After determining the number and location of shelters, decision-makers have to decide the type and number of evacuation vehicles, and find optimal evacuation routes to satisfy their objectives. Each evacuation vehicle has different capacities, transportation costs, and average velocities. While transporting evacuees to assigned shelters, there are also logistics flows of medical resources shipped from relief warehouses to the right shelter at the appropriate time. The underlying structure of the proposed evacuation network is presented in Figure 1, including the location sets along with the flows. Next, we proceed with a discussion on the simulation model of the problem of interest.

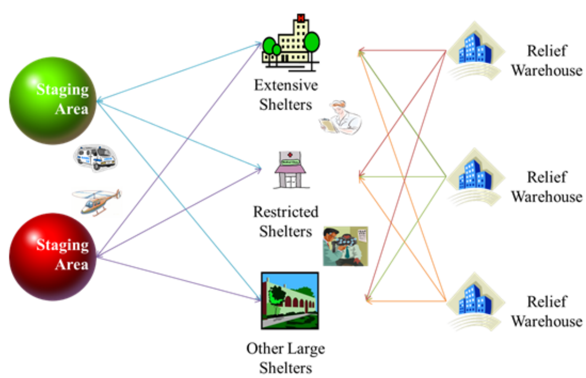

Figure 1: Underlying structure of the proposed evacuation network.

We propose an ABDES evacuation framework based on an embedded GIS module to solve the LSND evacuation network problem that involves multiple candidate shelters, multi-priorities patients, and multiple vehicle types. Figure 2 shows the overall evacuation framework that consists of 3 interacting components: a disaster scenario generator (DSG) module, a GIS module for analyzing an evacuation network under discussion, and a simulation module based on the ABDES approach. The DSG module produces the type and scale of the natural disaster, principal parameters for the model as well as various geographic information of the affected region. The scenario is generated based on the type of LSND to be modeled and analyzed. Several scenarios with nonfunctional shelters or relief warehouses and inaccessible road conditions can be also constructed by the DSG module. However, such cases are beyond the scope of this paper. With the information generated from the DSG module, the GIS module models and solves the basic crux of the evacuation problem, which is the location and number of shelters for the evacuation. After analyzing the affected areas, the GIS module determines the optimal shelters for satisfying the goals of the problem. ArcMAP 10.1 and ArcGIS network analyst extension methodology are used in the GIS module. Finally, from the ABDES module, we can determine the optimal evacuation routes and the relevant results. The agents can perceive their operations and surrounding environment based on the predefined rules. In this paper, there are two different agents - patients and vehicles. The ABDES module is constructed using ARENA 14.0.

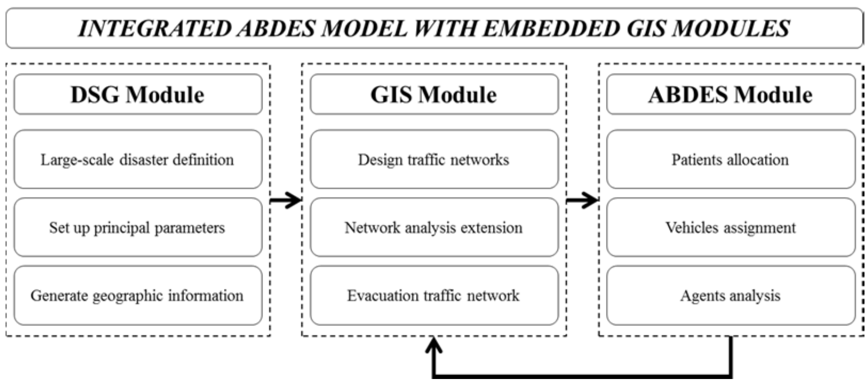

Figure 2: Overall evacuation framework with three modules.

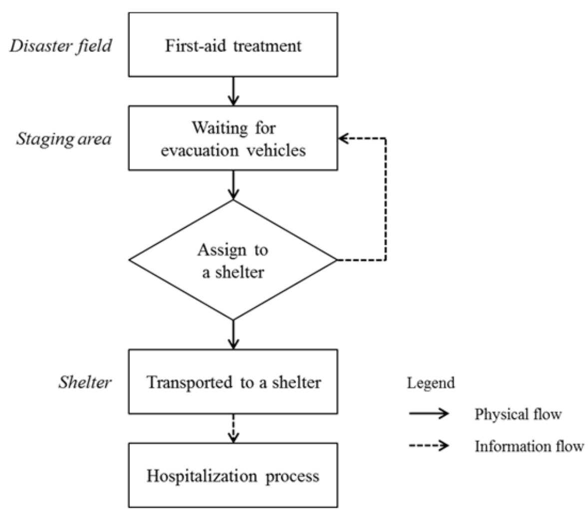

Figure 3: Flowchart of patient agents transported to shelters.

We consider decision rules to simulate the flow of each individual patient and vehicle during the entire evacuation procedure. Patients are moved to staging areas instantly when they are found by rescue workers. They are prioritized in the staging areas based on their severity levels. After staying and receiving first-aid treatment in a staging area, patients need to be transported to a proper shelter by a suitable vehicle. If a patient with a lower priority is waiting for a long time at a staging area and cannot be transported to a shelter, then the patient's priority can be changed to a higher priority (Gong and Batta 2006). However, in this paper, we assume that the priority of patients does not change with time. When patients are allocated to a shelter, there exist several considerations such as capacities of vehicles and the designated shelter, traffic states of routes from staging areas to shelters as well as suitability of evacuation vehicles (for example, on some occasions, an evacuation vehicle can transport only low-priority patients.). The number of patients to accommodate in each evacuation vehicle is also different based on the priority of the patients. For example, an evacuation vehicle such as an ambulance can accommodate two first-priority patients while another evacuation vehicle can transport more than three lower priority patients . While transporting patients to shelters, the decision-makers have to consider the transportation costs of evacuation vehicles arising from traffic congestion situations, any change of patients' condition or unexpected accidents. When patients arrive at a shelter, the patients have to go through the hospitalization process. The procedure and elapsed time is different based on the priority of patients. Figure 3 and 4 describe the agent flow of each patient and each vehicle in the model during the entire evacuation process, respectively.

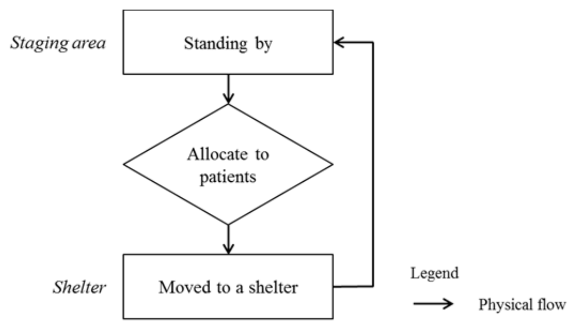

Figure 4: Flowchart of vehicle agents during evacuation.

4 EXPERIMENT AND RESULT ANALYSIS

Numerical experiments are conducted for a LSND evacuation problem in this section. The purpose of the experiments is twofold: (i) to explore the applicability and performance of the proposed model in a large-scale evacuation network, and (ii) to evaluate the potential merits and deficiencies of implementing resulting optimized evacuation plans in a possible LSND problem instance. We examine the efficiency and the effectiveness of the integrated ABDES evacuation framework based on an embedded GIS module through some comprehensive computational experiments.

The proposed model is performed on a LSND evacuation network that has 2 staging areas, 2 existing shelters, 6 candidate shelters, 2 relief warehouses, 100 evacuation vehicles, 3 patient-priority types, 2 evacuation vehicle types, and 3 relief resource types. In particular, 6 candidate shelters are classified as 3 restricted shelters and 3 other large shelters without medical infrastructure in the network. The city of Galveston, Texas is used as an example for designing the LSND evacuation network. Galveston is located on Galveston Island, a barrier island off the Texas Gulf coast near the mainland. The city is about 45 miles southeast of downtown Houston. The Galveston causeway is the only major road connected to neighborhood areas. If the Galveston causeway is rendered unusable by a LSND, there are few routes to transport evacuees to nearby areas. Given these characteristics of the city of Galveston, it is necessary to establish an evacuation strategy in the event of a LSND.

In the experiment, we consider a short-notice natural disaster such as a hurricane that has a desirable lead time of around 24 hours. This is because decision-makers are required to develop alternate tactical evacuation strategies based on the expected spatial-temporal influence of impending natural disasters. If necessary, decision-makers can establish an alternate evacuation plan approximately every 24 hours. All of the time period intervals are in 1-minute increments, and the whole evacuation time is set as 48 hours in our experiment. The number of evacuation vehicles consists of 90 ambulances and 10 helicopters.

ArcMAP 10.1 is used to prepare maps and tables for Houston-Galveston areas in Texas. The raw data used in this experiment is generated from the existing geographic databases provided by ESRI. For this experiment, all of the geographic information related to the Houston-Galveston areas is obtained from the

Houston-Galveston Area Council (H-GAC) (2014). The DSG module is designed to be capable of interacting with resource archives of GIS data for the purpose of scenario extraction. With the scenario information generated from the DSG module, the ABDES module simulates the LSND evacuation network problem. At this point, in order to simulate it on a real map, we require a CAD file version of the result map because only CAD or VISIO files can be imported into the ARENA. The result map is exported to a CAD file from the ArcMap 10.1 using Python, which is subsequently imported into the ARENA. As a result, ArcMap 10.1 produces a geodatabase design on the basis of the ESRI resources service and H-GAC GIS library (Figure 5).

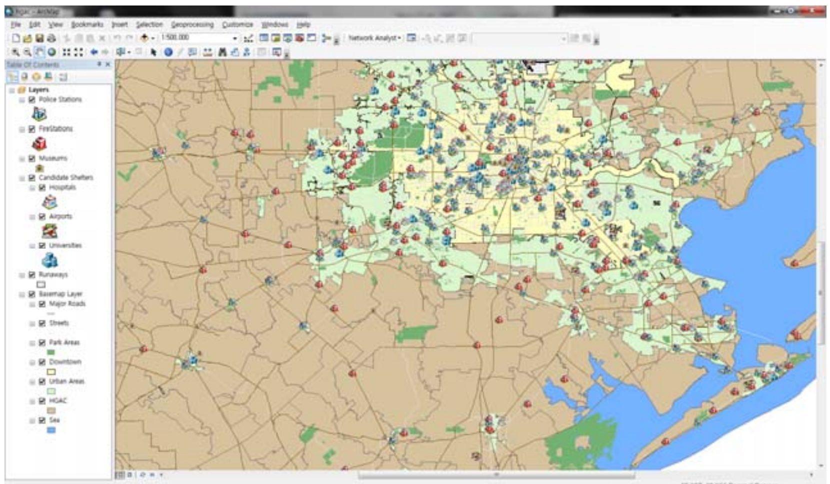

Figure 5: Geodatabase design of the Houston-Galveston region.

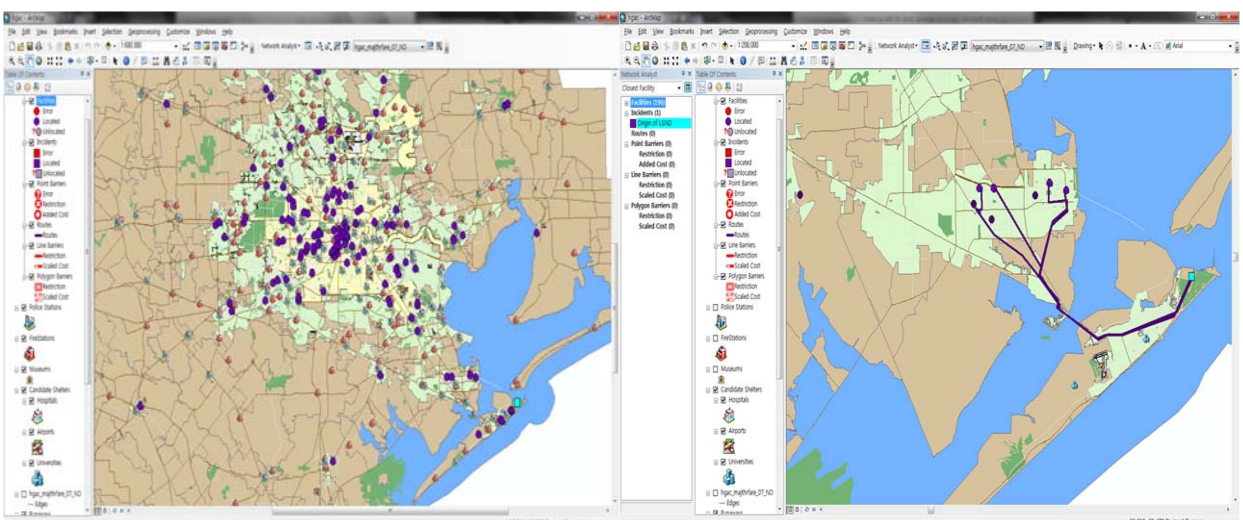

Figure 6: Evacuation shelters selected by ArcGIS network analyst extension.

Finally, the initial evacuation shelters are selected satisfying the geographic and transportation restrictions by using the ArcGIS network analyst extension that can build a network dataset and perform analyses on a network dataset (Figure 6). Subsequently the ABDES model finds an effective evacuation plan where patients are allocated and evacuation vehicles are assigned by the evacuation plan, and makes efficient logistics flow decisions for shipping relief resources to the appropriate shelters. Some images, icons and clips inform healthcare and transportation areas are used in the modeling of our problem for visualization purposes. Figure 7 shows a simulation implementation screen using ARENA 14.0.

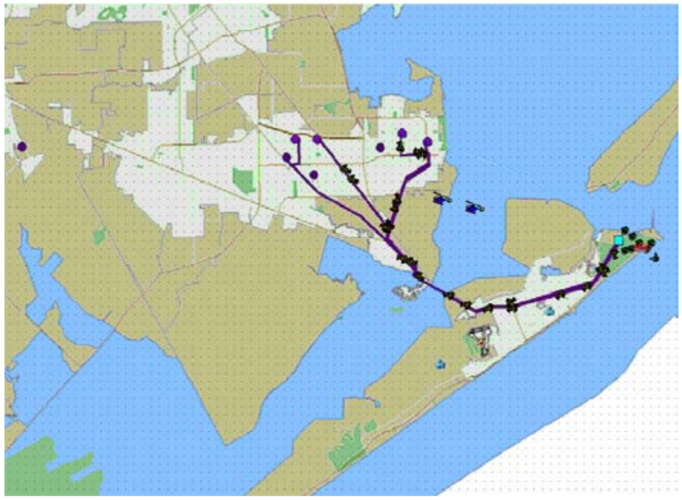

Figure 7: Simulation implementation screen.

The comprehensive simulation results are summarized in Table 1. The scenario generated from the DSG module is Scenario 1. Each scenario is run for 1,000 replications. The total evacuation cost is \$2.78M based on our cost estimates for the experiment, and the number of evacuees is 6,835 (out of 10,000). All the patients cannot be transported to shelters based on the total evacuation period of two days. In this scenario, 6,835 patients are receiving treatment in shelters.

Table 1: Principal simulation results.

		Scenario 1	**Scenario 2**	**Scenario 3**
Total evacuation cost (US\$M)		2.78	3.35	3.12
The number of patients	evacuees	6,835	8,538	9,465
	in shelters	6,114	7,716	8,635
	discharged	721	822	830
The number of patients (In/Out)	1st priority	1,485/143	1,476/137	1,457/127
	2nd priority	3,463/260	3,491/318	3,492/283
	3rd priority	5,052/318	5,033/367	5,051/420
Average waiting time for evacuating	1st priority	6.17 min	5.79 min	4.90 min
	2nd priority	11.45 min	11.38 min	12.78 min
	3rd priority	25.83 min	23.55 min	24.97 min
Utilization of EMT nurses	Staging area 1	99.92%	75.55%	87.91%
	Staging area 2	100.00%	76.05%	89.03%
Utilization of vehicles		98.71%	98.17%	93.45%

The utilization of emergency medical technician (EMT) nurses is 99.9% in staging area 1 and 100% in staging area 2. The utilization of evacuation vehicles is 98.71% during the evacuation. It is obvious that the number of nurses and evacuation vehicles require to be changed given the extremely high utilization rates of the resources. Changing levels of utilization of EMT nurses and vehicles are being considered in the different scenarios. The desired levels of the utilization is not discussed in this paper, but a tactical planning for improving the utilization is suggested. Scenario 2 has 100 ambulances and 20 helicopters, and 2 nurses are added to each shelter. The total evacuation cost and the number of evacuees in Scenario 2 increases by 20.50% and 24.92% compared to Scenario 1, respectively. In terms of the utilization, the utilization of EMT nurses and vehicles in Scenario 2 reduces by 24.39% (staging area 1), 23.95% (staging area 2), and 0.55%, respectively. In the third scenario, Scenario 3, there are 6 EMT nurses in each staging area and 140 vehicles consisting of 110 ambulances and 30 helicopters. The total evacuation cost increases by 12.23% compared to Scenario 1, and reduces by 6.87% compared to Scenario 2. The number of evacuees in Scenario 3 increases by 38.48% and 10.86% compared to Scenarios 1 and 2, respectively. The utilization of vehicles and EMT nurses improves as well. Based on the estimated results from the three experiments, we find that Scenario 3 is the best situation.

The integrated model offers valuable insights into the operational characteristics of each evacuation shelter. For instance, in our experimental analysis, Scenario 3 has 5 evacuation shelters, and the average waiting time of each patient (regardless of the patient priorities) and the rate of patient hospitalization in a shelter, which is referred to as the circulating rate, is the highest in shelter A among all shelters (Figure 8). This is a representative feature of a large hospital, which could indicate to the decision maker that shelter A may need to increase the staffing level. In contrast, the opposite phenomenon is occurred in shelter E. This is because shelter E is a restricted shelter, which can be a small clinic or a medical center. Using the information, the decision maker can possibly analyze redistribution of resources from one shelter to another. The trend in the staff utilization level across the five shelters can also be seen in Figure 8.

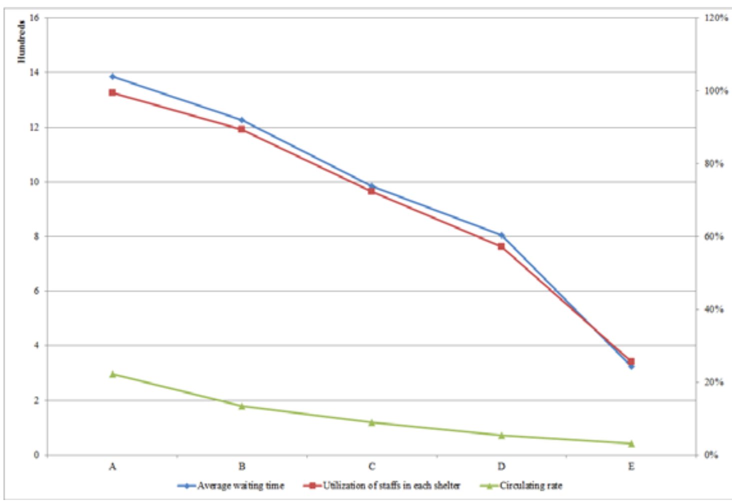

Figure 8: Results analysis of Scenario 3.

5 CONCLUSIONS AND FUTURE WORKS

In this paper, we have addressed a LSND evacuation simulation modeling with a complex existing road network. An ABDES evacuation framework based on an embedded GIS module is proposed to determine an optimal assignment of evacuees, allocation of evacuation vehicles, location of shelters, and logistics flow of medical resources. A GIS methodology is applied to the proposed evacuation framework for the setting of more realistic spatial parameters. Furthermore, in order to examine the applicability and extensibility of the proposed simulation model, we conduct a comprehensive computational experiment using a large-scale realistic instance based on the city of Galveston, Texas.

In conclusion, we believe that our proposed evacuation framework can serve as the foundation for a LSND evacuation decision support system. This would involve extensive collaboration with emergency management experts to develop a system to meet their needs.

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