SHELTERING PLANNING AND MANAGEMENT FOR NATURAL DISASTERS

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Abstract

A two-stage stochastic program is constructed to study sheltering network planning and operations for natural disaster preparedness and responses. The preparedness phase decides the locations, capacities and held resources of new Permanent Shelters. Under each disaster scenario, evacuees and resources are allocated to shelters in the response phase to minimize the transportation, shortage, and surplus costs. To address the computational burden, the L-shaped algorithm is applied to decompose the program into the scenario level and each sub-problem is a linear program. A case study for hurricane preparedness and response in the Gulf Coast region of the U.S. is conducted to demonstrate the usage of the model and verify the fast convergence of the L-shaped algorithm.

1. Introduction

In May 2009, the U.S. Department of Homeland Security (DHS) announced a new national shelter system to help victims of natural disasters, especially evacuees of hurricanes (Gibson, 2009). The system would have a database of thousands of places for evacuees to go in an emergency. Currently, the Red Cross National Shelter System (NSS) keeps information regarding over 54,000 potential sheltering facilities and the information can be accessed by the Federal Emergency Management Agency (FEMA) (American Red Cross, 2009). However, most shelters in NSS are not specialized for evacuation and have other functions during regular time, such as churches, convention centers, stadiums, schools, etc. FEMA provides funding to upgrade some potential shelters to meet FEMA standards to provide mass and quality sheltering. In this paper, shelters that have already met FEMA standards are defined as Existing Permanent Shelters. All other shelters are Temporary Shelters. New Permanent Shelters could be built from the scratch or through an updating of current Temporary Shelters. The candidate sites of new Permanent Shelters are defined as Potential Permanent Shelter locations. FEMA has to decide how many new Permanent Shelters should be built during preparedness. Once a natural disaster is imminent, FEMA and the Red Cross need to decide which shelters are open and provide the relevant information to the public.

Numerous mathematical programming (e.g., Yamada 1996; Choi et al. 1988; Liu et al. 2006; Li et al. 2008), queuing (e.g., Bakuli and Smith 1996; Stepanov and Smith, 2009) and simulation models (e.g., Weinroth 1989; Drager et al. 1992; Tufekci 1995). Shelters play a critical role in response to massive natural disasters and several papers in the literature consider the locations of shelters in an evacuation process. The shelter locations could influence the total congestion-related evacuation time in hurricane response (Sheral et al., 1991). Yi and Özdamar (2007) used a mixed integer multi-commodity network flow model to decide the routes of shipping both resources and evacuees. Two-stage stochastic programming models could be used to plan the transportation of commodities to disaster-affected areas during response (Barbarosogcaronlu and Arda, 2004), to manage evacuation (Li et al., 2008), or to locate distribute centers of supplies in the preparedness (Rawls and Turnquist 2010).

2. Problem Statement and Model Formulation for Sheltering Network Planning and Operation Problem

The overall sheltering network planning and operation problem (SNPOP) is illustrated in Fig.1. In the middle layer, there are two Existing Permanent Shelters, three Temporary Shelters, and two Potential Permanent Shelter locations that could be selected to be new Permanent Shelters with certain capacities and resource inventory. After knowing the information of a specific natural disaster, transportation network condition and evacuee demands are assumed to be known. The second stage decides the evacuee assignment to shelters and the resource shipment from distribution centers to shelters. The two stages interact with each other so that this paper proposes a two-stage stochastic program to capture various scenarios.

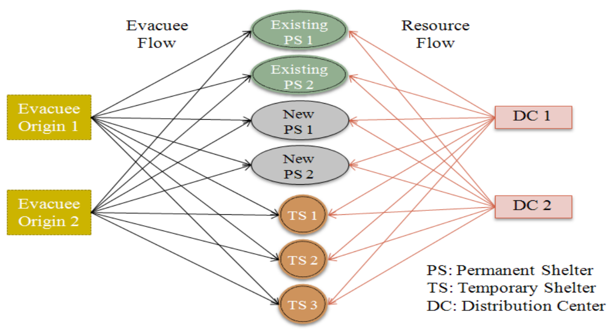

Figure 1 Illustration of SNPOP

The following information is assumed to be known as parameters for the SNPOP model.

ES (PS) : Set of Existing (Potential) Permanent Shelters;

TS : Set of Temporary Shelters;

S: Set of all shelters, $S = ES \cup TS \cup PS$;

K: Set of evacuee origins;

I : Set of distribution centers (or origins of resources), i is its index;

R: Set of resources (commodities or personnel) needed for sheltering, r is its index;

U_j^e: Capacity of Existing Permanent Shelter j in the number of evacuees, $j \in ES$;

U_j^t: Capacity of Temporary Shelter j in the number of evacuees, $j \in TS$;

a_{ir} : Available amount of commodity r at distribution center i;

h_{jr}^e: Available amount of commodity r at Existing Permanent Shelter j, $j \in ES$;

s_j^p: Fixed cost for a new Permanent Shelter at location j divided by the expected number of disasters in the study area during its expected lifetime, $j \in PS$;

e_r: Unit cost of holding resource r at location j per year divided by the expected number of disasters per year, $j \in PS$;

c^p: Unit capacity cost for one evacuee at Permanent Shelters divided by the expected number of disasters in the study area during shelters' expected lifetime, $j \in PS$;

Ω: Set of disaster scenarios, ω is its index;

$Prob(\omega)$: Probability of scenario ω;

$d_k(\omega)$: Total evacuees generated at demand point (affected area) k under scenario ω;

$v_{kj}(\omega)$: Cost of allocating one person from demand point k to shelter j (transportation cost plus operational cost of one evacuee at shelter j) under scenario ω;

$q_{ijr}(\omega)$: Cost of transporting one unit of commodity r from distribution center i to shelter j under scenario ω; and

b_r^+ (b_r^-): Unit cost of surplus (or shortage) for commodity *r* after evacuation.

Note that the units for all kinds of resources are normalized to the required amount for each evacuee during one disaster. The SNPOP model includes the following decision variables.

z_j^p: 1: If the Potential Permanent Shelter location *j* is chosen for setting up a new Permanent Shelter, 0: Otherwise, $j \in PS$;

U_j^p: Capacity of the Permanent Shelter at potential location *j*, $j \in PS$;

h_{jr}^p: Available amount of resource *r* at a Potential Permanent Shelter location *j*, $j \in PS$;

$x_{kj}(\omega)$: Number of evacuees transported from origin *k* to shelter *j* under scenario $\omega, j \in S$;

$y_{ijr}(\omega)$: Amount of commodity *r* shipped from distribution center *i* to shelter *j* under scenario $\omega, j \in S$;

$s_{jr}^+(\omega)$: Surplus amount for commodity *r* after evacuation at shelter *j* under scenario ω; and

$s_{jr}^-(\omega)$: Shortage amount for commodity *r* after evacuation at shelter *j* under scenario ω.

With the above definition of variables and parameters, the SNPOP model is given as follows.

$$\min \sum_{j \in PS} s_j^p z_j^p + \sum_{j \in PS} c^p U_j^p + \sum_{j \in PS} \sum_{r \in R} e_r h_{jr}^p + \sum_{\omega \in \Omega} Prob(\omega) \left\{ \sum_{k \in K} \sum_{j \in S} v_{kj}(\omega) x_{kj}(\omega) + \sum_{i \in I} \sum_{j \in S} \sum_{r \in R} q_{ijr}(\omega) y_{ijr}(\omega) + \sum_{j \in S} \sum_{r \in R} \left(b_r^+ \, s_{jr}^+(\omega) + b_r^- \, s_{jr}^-(\omega) \right) \right\} \quad (1)$$

$$\text{s.t. } U_j^p \leq M z_j^p \quad ; \quad (2)$$

$$\sum_{k \in K} x_{kj}(\omega) \leq U_j^t \quad ; \quad (3)$$

$$\sum_{k \in K} x_{kj}(\omega) \leq U_j^e \quad ; \quad (4)$$

$$\sum_{k \in K} x_{kj}(\omega) \leq U_j^p \quad ; \quad (5)$$

$$\sum_{j \in S} x_{kj}(\omega) = d_k(\omega) \quad ; \quad (6)$$

$$\sum_{j \in S} y_{ijr}(\omega) \leq a_{ir} \quad ; \quad (7)$$

$$\sum_{i \in I} y_{ijr}(\omega) - \sum_{k \in K} x_{kj}(\omega) = s_{jr}^+(\omega) - s_{jr}^-(\omega) \quad ; \quad (8)$$

$$\sum_{i\in I} y_{ijr}(\omega) + h^{e}_{jr} - \sum_{k\in K} x_{kj}(\omega) = s^{+}_{jr}(\omega) - s^{-}_{jr}(\omega) \quad ; \qquad (9)$$

$$\sum_{i\in I} y_{ijr}(\omega) + h^{p}_{jr} - \sum_{k\in K} x_{kj}(\omega) = s^{+}_{jr}(\omega) - s^{-}_{jr}(\omega) \quad ; \qquad 10$$

.

$$z^{p}_{j} \in \{0,1\}\ ;\ U^{p}_{j}, h^{p}_{jr}, x_{kj}(\omega), y_{ijr}(\omega), s^{+}_{jr}(\omega), s^{-}_{jr}(\omega)\ \in R^{n}_{+}$$

The objective function (1) minimizes the total first stage cost and the expected cost of the second stage over all scenarios. The first stage cost includes the fixed cost and the variable cost based on capacity to have new Permanent Shelters and the inventory cost of resources stored at new Permanent Shelters. All costs are normalized for a disaster. The second stage cost includes transportation costs of evacuees, transportation costs of resource distribution, and the surplus and shortage costs for resources after an evacuation. The first constraint set (2), where M is a big number, guarantees a new Permanent Shelter has to be established before it is used. Constraint sets (3-5) are capacity constraints of all three kinds of shelters. Constraint set (6) ships all evacuees to shelters. Constraint set (7) guarantees that the total shipment of resource r from distribution center i will not exceed the available amount at the center. Constraint sets (8-10) are used to obtain the shortage and surplus of each resource type. The capacity provided by all Temporary Shelters is huge because of their big number. Furthermore, the SNPOP model allows resource shortage and surplus at shelters. Therefore, the feasibility of the SNPOP is guaranteed under each scenario. The model has binary variables z^{p}_{j} in the first stage. The second-stage problem under each scenario ω formed by constraint sets (2-10) and the objective function of $\min \sum_{k\in K j\in S} v_{kj}(\omega)x_{kj}(\omega) + \sum_{i\in I, j\in S, r\in R} q_{ijr}(\omega)y_{ijr}(\omega) + \sum_{j\in S, r\in R}\left(b^{+}_{r}s^{+}_{jr}(\omega) + b^{-}_{r}s^{-}_{jr}(\omega)\right)$ is a linear program. Based on preliminary numerical experiments, the SNPOP with a real-world size cannot be solved by ILOG CPLEX 9.0 in a reasonable amount of time.

The computational challenge of solving the SNPOP model (1-10) is mainly caused by the large number of scenarios. The model could be rewritten as follows by separating the two stages of preparedness and response. The first-stage problem is:

$$\min \sum_{j\in PS} s^{p}_{j} z^{p}_{j} + \sum_{j\in PS} c^{p} U^{p}_{j} + \sum_{j\in PS}\sum_{r\in R} e_{r} h^{p}_{jr} + E_{\omega}[Q(U^{p}_{j}, h^{p}_{jr}, \omega)] \qquad (11)$$

s.t. constrain (2); .

Where $Q(U^{p}_{j}, h^{p}_{jr}, \omega)$ is the objective function value of the second stage with given values of U^{p}_{j} and h^{p}_{jr} and under a given scenario ω. The second-stage sheltering network problem under one particular scenario ω can be expressed as:

$$Q(U^{p}_{j}, h^{p}_{jr}, \omega) = \min \sum_{k\in K}\sum_{j\in S} v_{kj}(\omega)x_{kj}(\omega) + \sum_{i\in I}\sum_{j\in S}\sum_{r\in R} q_{ijr}(\omega)y_{ijr}(\omega) + \sum_{j\in S}\sum_{r\in R}\left(b^{+}_{r}\ s^{+}_{jr}(\omega) + b^{-}_{r}\ s^{-}_{jr}(\omega)\right) \qquad (12)$$

s.t. constraints (2-10) under scenario ω; $x_{kj}(\omega), y_{ijr}(\omega), s_{jr}^{+}(\omega), s_{jr}^{-}(\omega) \in R_{+}^{n}$.

The second-stage sub-problem is feasible because it is assumed that the total capacity of all shelters is enough for all evacuees under any scenarios and shortage and surplus of resources are allowed. The second-stage sub-problem is a linear program, so the recourse function of $E_{\omega}\left[Q\left(U_j^p, h_{jr}^p, \omega\right)\right]$ is continuous, convex, and piece-wise linear. Therefore, the whole stochastic program can be solved by building the combination of outer linearization of the recourse cost function (RCF) representing $E_{\omega}\left[Q\left(U_j^p, h_{jr}^p, \omega\right)\right]$ and by solving the master cost function (MCF) iteratively using a cutting plane method. This method is called the L-shaped method, which was developed by extending Dantzig-Wolfe decomposition of the dual problem and Bender's decomposition of the primal problem to the stochastic programming domain (Birge and Louveaux, 1997). The key point of the L-shaped algorithm is to represent $E_{\omega}[Q(U_j^p, h_{jr}^p, \omega)$ for any (U_j^p, h_{jr}^p) with a convex hull that is formed iteratively by solving the first-stage problem and the second-stage problem (12). The first-stage problem at iteration v is rewritten into (13).

$$\min \sum_{j\in PS} s_j^p z_j^p + \sum_{j\in PS} c^p U_j^p + \sum_{j\in PS}\sum_{r\in R} e_r h_{jr}^p + \theta \tag{13}$$

$$\text{s.t.} \quad U_j^p \le M z_j^p \qquad \forall j \in PS;$$

$$\theta \ge \theta^v + \sum_{j\in PS} \pi_j^{p,v}(U_j^p - U_j^{p,v}) + \sum_{j\in PS}\sum_{r\in R} \rho_{jr}^p (h_{jr}^{p,v} - h_{jr}^p) \qquad \forall v \in \{1,2,\dots,V\}; \tag{14}$$

.

$\theta^v = E_{\omega}\left[Q\left(U_j^{p,v}, h_{jr}^{p,v}, \omega\right)\right]$ is the expected value of objective function values of the second-stage problems over all scenarios at iteration v by solving model (12) for each scenario ω with $U_j^p = U_j^{p,v}$ and $h_{jr}^p = h_{jr}^{p,v}$. Assume the Simplex multipliers associated with constraint set (5) when solving model (12) are $\pi_j^{p,v}(\omega)$ and the simplex multipliers associated with constraint set (10) are $\rho_{jr}^{p,v}(\omega)$. Therefore, $\pi_j^{p,v} = \sum_{\omega} Prob(\omega)\pi_j^{p,v}(\omega)$ and $\rho_{jr}^{p,v} = \sum_{\omega} Prob(\omega)\,\rho_{jr}^{p,v}(\omega)$.

3. Case Study

To demonstrate the implementation of the SNPOP model and evaluate the effectiveness of the L-shaped algorithm, a case study is conducted for sheltering planning and operations against hurricanes in the Gulf Coast region of the U.S. which covers Louisiana, Mississippi, Alabama, and Florida. For hurricanes, the most overwhelmed areas are along the coast around the landfall. The impact is reduced quickly when a hurricane moves into inland. The number of evacuees generated in each area under each hurricane scenario is mainly decided by two factors: the landfall location and hurricane intensity. Klotzbach et al. (2009) predicted the probabilities of landfalls at the county level for eleven regions from Brownsville, TX to Eastport, ME based on all tropical cyclones, storms and hurricanes occurrences from 1880-2007. The historical data were from the North Atlantic hurricane database Reanalysis Project conducted by the Hurricane Research Division and the Atlantic Oceanographic and Meteorological Laboratory. When hurricane intensity increases, the affected area is larger and the number of evacuees increases. Like the project conducted by Klotzbach et al. (2009), this research classifies hurricanes based on the Saffir-Simpson Scale into three broad categories as Storm (tropical storm), Hurricane (category 1and 2 on the Saffir-Simpson Scale), and Intense Hurricane (category 3, 4 and 5 on the Saffir-Simpson Scale). The number of landfalls in each county k under category t during 1880-2007, N_t^k, is calculated as $L_t^{l_k} \cdot D_k$, where $L_t^{l_k}$ is the number of category t hurricanes that occurred in region l_k in which county k is located and D_k is the coastline distance of county k divided by region l_k's whole coastline distance. In this research, each scenario ω is characterized by a pair of (k, t), the landfall county k and hurricane category t. The probability of scenario ω is $Prob(\omega) = \frac{N_t^k}{\sum_{t,k} N_t^k}$. This case study considers all hurricane scenarios in which the landfall is between New Iberia, LA and Robertsdale, AL. A hurricane may affect neighboring counties, but the affected areas are restricted along the coastline. Table 1 provides affected counties with their landfall probabilities under each hurricane category. Note $K' \subset K$, where K' is the set of landfall counties and K is the set of all evacuee origins/affected areas. Table 2 lists the assumed percentage of population who will be evacuees in each county when a category t hurricane makes landfall in county k. This case study considers a total of 57 Existing Permanent Shelters and 26 Potential Permanent Shelter locations. Locations and capacities of Permanent Shelters are provided in Fig 2. The locations and capacities of the Existing Permanent Shelters are based on the published information from the state government of Louisiana and the American Red Cross (2009). The Potential Permanent Shelter locations are randomly selected at highly populated areas. As mentioned in Section 1, there are thousands of Temporary Shelters in the study region. It is not possible or necessary to consider individual Temporary Shelters separately. The authority just needs to decide how much Temporary Shelter capacity should be used in each area and open Temporary Shelters based on a priority table decided in the preparedness stage. This case study consolidates Temporary Shelters into 31 regions. The capacities are randomly created based on a uniform distribution U[10,000, 20,000]. Seven distribution centers and five resource types are considered in this case. The values of a_{ir} are randomly created based on a uniform distribution U[200,000, 250,000]. Some resources are assumed to be held already at Existing Permanent Shelters and the amount of resource r at shelter j, h_{jr}^e, is randomly drawn from a uniform distribution U[300, 700]. The cost of allocating one evacuee $v_{kj}(\omega) = LH_k(\omega) \cdot vb \cdot d_{kj}$, in which d_{kj} is the distance (in miles) from evacuee demand origin k to shelter j, vb is the unit transportation cost (in dollars per mile per evacuee), and $LH_k(\omega)$ is a scenario-based weight capturing the increased transportation costs of the affected areas because of possible infrastructure damages and traffic congestion. The values of $LH_k(\omega)$ are decided by uniform distributions in Table 3 when the landfall county is m and the hurricane category is t. For other counties, $LH_k(\omega) = 1$. This case study sets $vb = \$0.5$ per mile per person.

Table 1 Locations and population of affected areas and landfall/scenario probabilities

	County Index	County	Population (2007)	Storm Probability	Hurricane Probability	Intense Hurricane Probability	
Possible Affected Areas *K*	1	Cameron, LA	7,238				
	2	Abbeville, LA	56,096				
	3	New Iberia, LA	74,965	0.03162	0.01551	0.00699	Possible Landfall Areas *K*'
	4	Franklin, LA	51,311	0.04278	0.02098	0.00946	
	5	Houma, LA	108,424	0.08835	0.04333	0.01954	
	6	Thibodaux, LA	92,713	0.03162	0.01551	0.00699	
	7	Hahnville, LA	52,044	0.02581	0.01266	0.00571	
	8	Gretna, LA	423,520	0.01674	0.00821	0.00370	
	9	Pointe a la Hache, LA	21,540	0.04836	0.02372	0.01069	
	10	Chalmette, LA	19,826	0.04371	0.02143	0.00967	
	11	New Orleans, LA	239,124	0.03139	0.01539	0.00694	
	12	Covington, LA	226,625	0.04255	0.02086	0.00941	
	13	Woodville, MS	40,421	0.02604	0.01277	0.00576	
	14	Bay St. Louis, MS	171,875	0.03441	0.01687	0.00761	
	15	Pascagoula, MS	130,577	0.03813	0.01870	0.00843	
	16	Mobile, AL	406,309	0.03441	0.01687	0.00761	
	17	Robertsdale, AL	174,439	0.04836	0.02372	0.01069	
	18	Pensacola, FL	37,600				
	19	Milton, FL	147,044				

Table 2 Percentage of evacuees when a category t hurricane makes landfall in county k

Hurricane Category	County Index				
	k-2	k-1	k	k+1	k+2
t=1	0	5%	10%	5%	0%
t=2	0	10%	20%	10%	0%
t=3	20	50%	70%	50%	20%

Table 3 $LH_k(\omega)$ values when a category *t* hurricane makes landfall in county *m*

Hurricane Category	County Index *k*				
	m-2	*m*-1	*m*	*m*+1	*m*+2
t=1	1	U(1.00, 1.10)	U(1.20, 1.25)	U(1.00, 1.10)	1
t=2	1	U(1.05, 1.15)	U(1.25, 1.35)	U(1.05, 1.15)	1
t=3	U(1.05, 1.15)	U(1.30, 1.35)	U(1.40, 1.45)	U(1.30, 1.35)	U(1.05, 1.15)

Because Permanent Shelters are usually preferred over Temporary Shelters, additional cost, randomly drawn from U[100,110], is considered for evacuees going to a Temporary Shelter and is added into $v_{kj}(\omega)$, $j \in TS$. The resource shipping cost is $q_{ijr}(\omega) = LH(\omega) \cdot rvb_r \cdot d_{ij}$. The transportation cost per unit per mile, rvb_r, is assumed to be different for resources, and their values are given in Table 4. The table also lists the unit surplus cost and shortage cost at shelters after an evacuation process and the unit holding cost at Permanent Shelters for each resource type. Here, the values of rvb_r, v_r^+, v_r^-, and e^r are randomly created based on uniform distributions of U[0.1, 0.2], U[40, 70], U[50, 80], and U[20,70] respectively.

Table 4 Unit transportation cost, surplus cost, and shortage cost for resources

	Resource Type				
	1	2	3	4	5
Unit Transportation Cost (rvb_r) ($ per unit per mile)	0.11	0.12	0.15	0.1	0.14
Unit Surplus Cost (v_r^+) ($ per unit)	40	66	63	58	70
Unit Shortage Cost (v_r^-) ($ per unit)	57	70	63	53	57
Unit Holding Cost at Permanent Shelters (e^r) ($ per unit)	40	38	48	28	31

The case is solved with the L-shaped algorithm coded in Microsoft C++ on a Dell desktop with Intel® Core (TM) 2 CPU, 6600 @ 2.40 GHz and 2.00 GB of RAM by calling the optimization solver of CPLEX 9.0 for solving the master and sub-problems. The algorithm reaches the optimal solution of $21,824,600 after 206 iterations and 3,509 seconds. The result is illustrated in Fig. 2, a map created by Google Earth©. The map displays the distribution of all shelters, distribution centers and affected areas. The information about Existing Permanent Shelters include shelter name, location, and capacity are sourced from American Red Cross National Shelter System. The solution selects 6 out of 26 potential locations to build new Permanent shelters to build new Permanent Shelters. Fig. 3, also created by Google Earth©, illustrates the recommended evacuee flows and resource flows under scenario 45, in which an intense (Category 3) hurricane makes landfall in county 17 and affects counties 15 through 19.

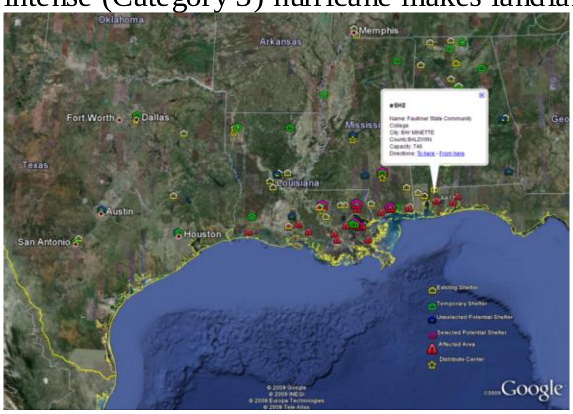

Figure 2 Case Study Solution

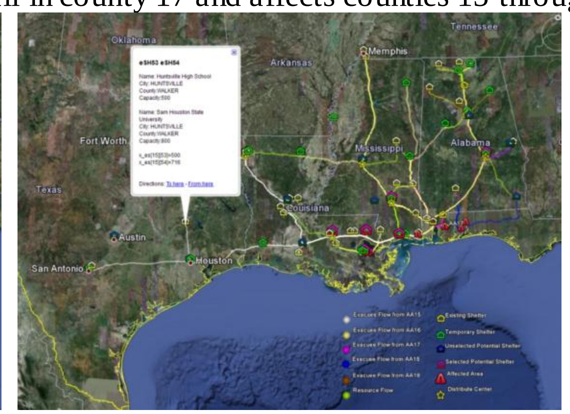

Figure 3 One scenario of evacuation process

4. Conclusion

This paper considers sheltering network planning in the preparedness stage and operations in the response stage for national disasters, especially for hurricanes, with a two-stage stochastic programming model with integer variables in the first stage. The first-stage master problem captures the planning problem while the second-stage sub-problems deal with the response problem under all possible scenarios. Because of the large size, the stochastic pro gramming model cannot be solved directly with existing optimization solvers. Therefore, this paper adopts the L-shaped algorithm to separate the two stages and solve the second-stage sub-problems individually with iterations. A comprehensive case study for hurricanes in the Gulf Coast region is presented. Each hurricane scenario is characterized by its landfall and intensity. The data collection includes the definition of scenarios with probabilities, the location and capacity information of Existing Permanent Shelters, and various cost components. The numerical experiment results show that the L-shaped algorithm converges well and a real-world problem could be solved in a reasonable amount of time. Though the case study could be solved within thousands of seconds, the computational burden could still be an issue if we increase the number of scenarios further to capture more stochastic feature of disasters or increase the resolution of the problem from counties to smaller areas. A future direction is to develop a more efficient algorithm to solve each sub-problem.

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