Sheltering Network Planning and Management Responding to Natural Disasters with a Case Study for Hurricane Evacuation at the Gulf Coast Region

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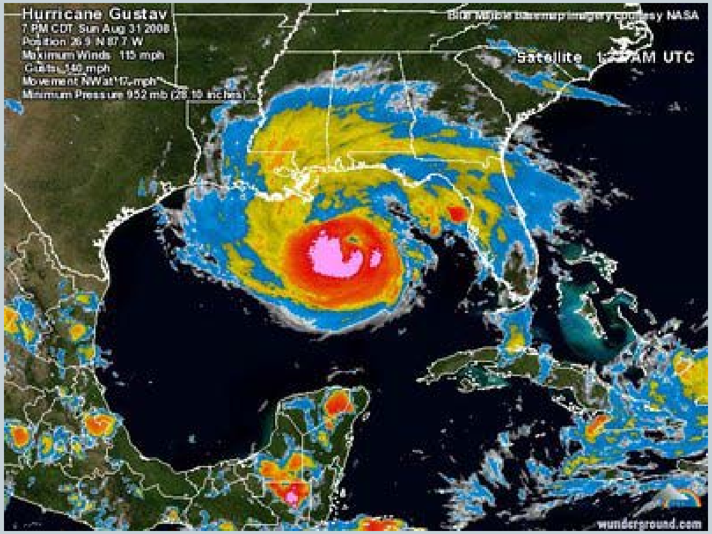
Outlines

- Introduction
- Literature Review
- Problem Statement
- Two-Stage Stochastic Program for Sheltering Network Design and Operations
- Solution Approaches
- Case Study
- Conclusion

1. Introduction

1.1 Background

- Sheltering network management is a decision-making process that tries to handle emergency evacuation problems.



Impact of Hurricane Gustav
Source: www.listenuptv.com

Impact of Hurricane Katrina
Source: www.listenuptv.com

1. Introduction
1.1 Background

- The process involves two types of decisions
  - Preparedness
  - Response
- The preparedness activities
  - Shelter location selection
  - Capacity assignment
- Response with information of a disaster
  - Evacuee transportation
  - Logistic support

Red Cross Permanent Shelter
Source: www.southmredcross.org

Source: www.sterlingtrucks.com

1. Introduction

1.2 Objective

- Build Sheltering Network Model
- Develop algorithm
- Study a real evacuation case

2. Literature Review

- Choi et al. (2003) generated an evacuation model based on network flow models with side constraints for restricted arc capacities.
- Yamada (1996) modeled a city emergency evacuation planning problem as two network flow problems for evacuee flows.
- Bakuli and Smith (1996) extended traditional state-dependent queuing networks into nonlinear unconstrained problems.
- Li et al. (2008) developed a two-stage stochastic evacuation model that considers traffic allocation.
- Lodree and Taskin (2007) solved a proactive disaster recovery planning problem using a dynamic method.
- Talebi and Smith (1985) provided a method for stochastic closed queuing network for analyzing hospital evacuation.
- Weinroth (1989) developed a simulation model called MOBILIXE for modeling a complex and large scale building evacuation problem.
- Drager et al. (1992) provided a model called EVACSIM to study escape and rescue activities on vessels.

3. Problem Statement

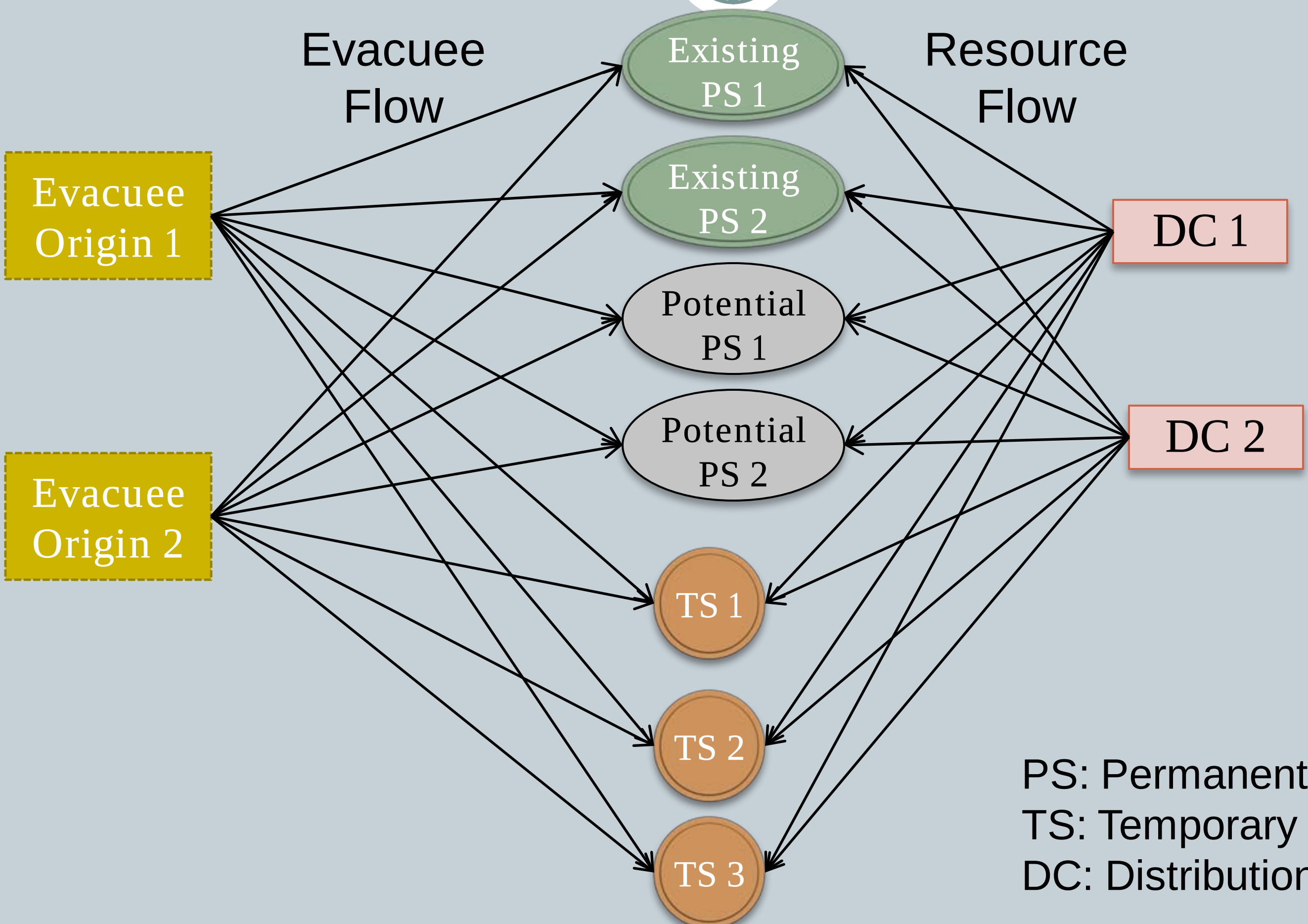
- Suffering Areas
- Shelters
- Distributions Centers
- Evacuees
- Resources
- Scenarios

3. Problem Statement

- During the preparedness stage
  - The location and capacity of permanent shelters

- After knowing information about one specific disaster
  - Evacuee transportation to shelters, both permanent and temporary ones
  - Logistics support

3. Problem Statement



PS: Permanent Shelter
TS: Temporary Shelter
DC: Distribution Center

4. A Two-Stage Stochastic Program

4.1 Parameters

ES : Set of existing permanent shelters;
PS : Set of potential permanent shelter locations;
TS : Set of temporary shelter candidate locations; ($TS \cap PS = \emptyset$);
S: $S = ES \cup TS \cup PS$;
I : Set of distribution centers, i is its index;
R: Set of resources (commodities or human resources) needed for sheltering, r is its index;
O: Set of evacuee origins;
s_j^p: Fixed cost of setting up a new permanent shelter at location j, $j \in PS$;
e_r: Unit cost of holding resource r at location j, $j \in PS$;
a_{ir} : Available amount of commodity r at distribution center i;
h_{jr}^e : Available amount of commodity r at an existing permanent shelter at location j, $j \in ES$;
c^p : Unit cost of having capacity for one evacuee at permanent shelters;
U_j^t : Capacity of temporary shelter j in the number of evacuees, $j \in TS$;
U_j^e : Capacity of permanent shelter j in the number of evacuees, $j \in ES$;
Ω Set of scenarios, ω is its index;
$p(\omega)$ 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) under scenario ω;
$q_{ijr}(\omega)$: Cost of transporting one unit of commodity r from distribution center i to shelter j under scenario ω;
b_r^+ : Unit cost of surplus for commodity r after evacuation;
b_r^- : Unit cost of shortage for commodity r after evacuation;

4. A Two-Stage Stochastic Program

4.2 Decision Variables

z_j^p: 1: If the location j is chosen for setting a 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 evacuee origin k to shelter j under scenario $\omega, j \in PS \cup ES \cup TS$;

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

$s_{jr}^{+}(\omega)$: Surplus amount for commodity r at shelter j considering scenario ω;

$s_{jr}^{-}(\omega)$: Shortage amount for commodity r at shelter j considering scenario ω;

4. A Two-Stage Stochastic Program

4.3 Model

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

s.t.

Permanent shelters

$$U_j^p \le M z_j^p \qquad \forall j \in PS; \qquad (2)$$

Shelter Capacities

$$\sum_{k\in O} x_{kj}(\omega) \le U_j^t \qquad \forall j \in TS, \forall \omega \in \Omega; \qquad (3)$$

$$\sum_{k\in O} x_{kj}(\omega) \le U_j^e \qquad \forall j \in ES, \forall \omega \in \Omega; \qquad (4)$$

$$\sum_{k\in O} x_{kj}(\omega) \le U_j^p \qquad \forall j \in PS, \forall \omega \in \Omega; \qquad (5)$$

Evacuee Demand

$$\sum_{j\in S} x_{kj}(\omega) = d_k(\omega) \qquad \forall k \in O, \forall \omega \in \Omega; \qquad (6)$$

4. A Two-Stage Stochastic Program

4.3 Model

Resource Availability

$$\sum_{j \in S} y_{ijr}(\omega) \leq a_{ir} \qquad \forall i \in I, \forall r \in R, \forall \omega \in \Omega; \qquad (7)$$

Shortage/Surplus

$$\sum_{i \in I} y_{ijr}(\omega) - \sum_{k \in K} x_{kj}(\omega) = s_{jr}^{+}(\omega) - s_{jr}^{-}(\omega) \qquad \forall j \in TS, \forall r \in R, \forall \omega \in \Omega; \qquad (8)$$

$$\sum_{i \in I} y_{ijr}(\omega) + h_{jr}^{e} - \sum_{k \in K} x_{kj}(\omega) = s_{jr}^{+}(\omega) - s_{jr}^{-}(\omega) \qquad \forall j \in ES, \forall r \in R, \forall \omega \in \Omega; \qquad (9)$$

$$\sum_{i \in I} y_{ijr}(\omega) + h_{jr}^{p} - \sum_{k \in K} x_{kj}(\omega) = s_{jr}^{+}(\omega) - s_{jr}^{-}(\omega) \qquad \forall j \in PS, \forall r \in R, \forall \omega \in \Omega; \qquad (10)$$

$$z_j^p \in \{0,1\}, U_j^p, h_{jr}^p, x_{kj}(\omega), y_{ijr}(\omega), s_{jr}^{+}(\omega), s_{jr}^{-}(\omega) \in R_{+}^{n}.$$

5. Solution Approaches

- MIP problem
  - A large number of variables, constraints and scenarios.
- L-Shaped Method
  - Decompose a large-size scale problem.
  - Several iterations to converge.
  - Provide solution bounds even optimal solution is unavailable.
- Network Flow Problem with Equal Flows for each sub-problem

5. Solution Approaches: Master Problem

$$\min \sum_{j \in PS} s_j^p z_j^p + \sum_{j \in PS} c^p U_j^p + \sum_{j \in PS} \sum_{r \in R} c_r h_{jr}^p + E_\xi Q(U_j^p, h_{jr}^p, \xi) \qquad (11)$$

s.t. $U_j^p \leq M z_j^p \qquad \forall j \in PS$

$z_j^p \in \{0,1\}, U_j^p, h_{jr}^p \in R_+^n.$

5. Solution Approaches: Second Stage

$$
\begin{aligned}
\text{Min} \quad & \sum_{k\in K}\sum_{j\in S} v_{kj}\, x_{kj} + \sum_{i\in I}\sum_{j\in S}\sum_{r\in R} q_{ijr}\, y_{ijr} + \sum_{j\in S}\sum_{r\in R}\left(b_r^+\, s_{jr}^+ + b_r^-\, s_{jr}^-\right)) \\
\text{s.t.} \quad & \sum_{k\in O} x_{kj}(\omega) \le U_j^t && \forall j \in TS, \forall \omega \in \Omega; \\
& \sum_{k\in O} x_{kj}(\omega) \le U_j^e && \forall j \in ES, \forall \omega \in \Omega; \\
& \sum_{k\in O} x_{kj}(\omega) \le U_j^p && \forall j \in PS, \forall \omega \in \Omega; \qquad (12) \\
& \sum_{j\in S} x_{kj}(\omega) = d_k(\omega) && \forall k \in O, \forall \omega \in \Omega; \\
& \sum_{j\in S} y_{ijr}(\omega) \le a_{ir} && \forall i \in I, \forall r \in R, \forall \omega \in \Omega; \\
& \sum_{i\in I} y_{ijr}(\omega) - \sum_{k\in K} x_{kj}(\omega) = s_{jr}^+(\omega) - s_{jr}^-(\omega) && \forall j \in TS, \forall r \in R, \forall \omega \in \Omega; \\
& \sum_{i\in I} y_{ijr}(\omega) + h_{jr}^e - \sum_{k\in K} x_{kj}(\omega) = s_{jr}^+(\omega) - s_{jr}^-(\omega) && \forall j \in ES, \forall r \in R, \forall \omega \in \Omega; \\
& \sum_{i\in I} y_{ijr}(\omega) + h_{jr}^p - \sum_{k\in K} x_{kj}(\omega) = s_{jr}^+(\omega) - s_{jr}^-(\omega) && \forall j \in PS, \forall r \in R, \forall \omega \in \Omega; \\
& h_{jr}^p, x_{kj}(\omega), y_{ijr}(\omega), s_{jr}^+(\omega), s_{jr}^-(\omega) \in R_+^n.
\end{aligned}
$$

5. Solution Approaches: Master Problem with Cuts

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

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

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

$z_j^p \in \{0,1\}, U_j^p, h_{jr}^p, \theta \in R_+^n.$

5. Solution Approaches: L-Shaped Algorithm

Step 0. $V = 0$ and $UB^0 = \infty$.

Step 1. Solve the master problem (13) and let $V = V + 1$.

Step 2, Let the objective function value be LB^V (the lower bound of the SNPOP model), obtain the values of U_j^p and h_{jr}^p from the solution in step 1 and set them as $U_j^{p,V}$ and $h_{jr}^{p,V}$, and let $UB^V = \sum_{j \in PS} s_j^p z_j^p + \sum_{j \in PS} c^p U_j^p + \sum_{j \in PS} \sum_{r \in R} e_r h_{jr}^p$ under the current solution from step 1.

Step 3. If $LB^V < \min_{v=0,\ldots,V-1} UB^v$, continue; otherwise, go to step 6.

Step 4. Solve model (12) individually for each scenario ω with $U_j^p = U_j^{p,V}$ and $h_{jr}^p = h_{jr}^{p,V}$, obtain θ^V, $\pi_j^{p,V}$, and $\rho_{jr}^{p,V}$, and let $UB^V = UB^V + \theta^v$ as the upper bound of the SNPOP problem.

Step 5. Add the cut of $\theta \geq \theta^V + \sum_{j \in PS} \pi_j^{p,V} (U_j^p - U_j^{p,V}) + \sum_{j \in PS} \sum_{r \in R} \rho_{jr}^{p,V} (h_{jr}^{p,V} - h_{jr}^p)$ into (13) and go to step 1.

Step 6. Stop with the optimal solution.

6. Case Study

6.1 Data Description (Scenario Definition)

- How to define scenarios?
  - Hurricane intensity based on the Saffir-Simpson Scale

    1. Storm (tropical storm)

    2. Hurricane (category 1 and 2)

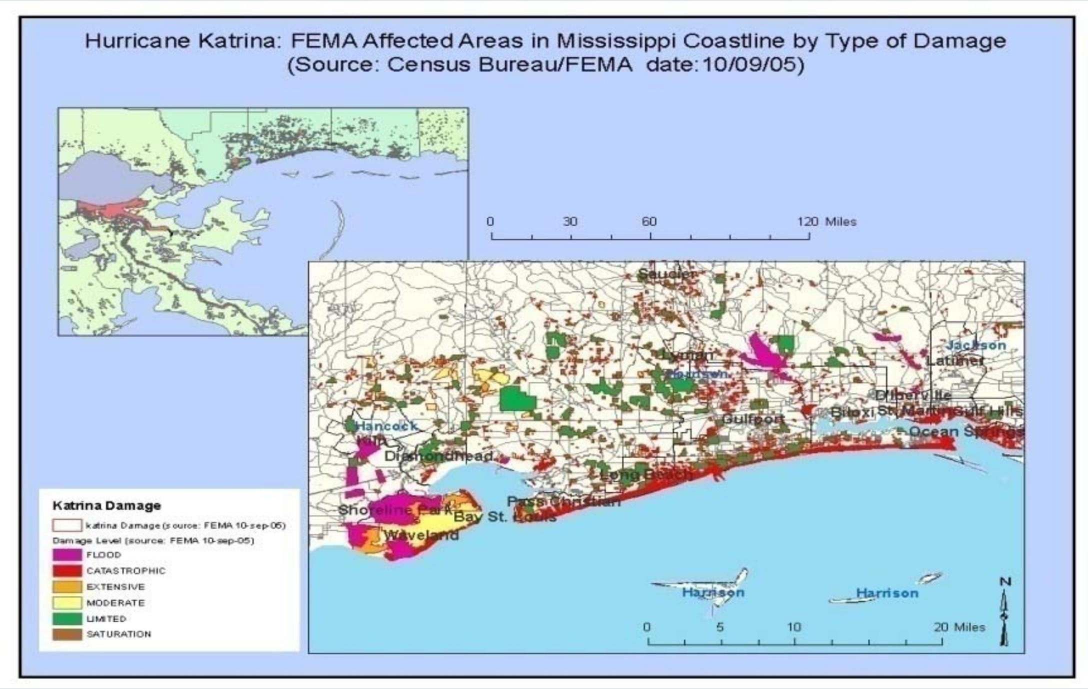
    3. Intense Hurricane (category 3, 4 and 5).
  - Hurricane landfalls

6. Case Study

6.1 Data Description

- Why landing points are important?

Usually, the hurricane/ storm landfall areas are the disaster affected areas.



6. Case Study

6.1 Data Description

- How to identify hurricane landing points with probabilities?
  - Categorize all possible landfalls in a region based on unit of a county (Klotzbach et al.).
  - The landfall probabilities based on past occurrences from 1880 to 2007.
  - The historical data from HURDAT Reanalysis Project conducted by Hurricane Research Division (HRD), Meteorological Laboratory (AOML), and the Atlantic Oceanographic.

6. Case Study

6.1 Data Description

	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				

6. Case Study
6.1 Data Description

Table 2 Percentage of Evacuees when a Category *t* Hurricane Landfalls 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 Locations and Capacities of Temporary Shelters

New Orleans, LA 19,859	Baton Rouge, LA 16,043	Shreveport, LA 12,428	Metairie, LA 18,028
Lafayette, LA 14,200	Lake Charles, LA 15,920	Kenner, LA 18,350	Bossier City, LA 16,365
Monroe, LA 17,305	Alexandria, LA 12,783	Jackson, MS 19,791	Gulfport, MS 17,498
Biloxi, MS 19,719	Hattiesburg, MS ,19,874	Greenville, MS 11,080	Meridian, MS 15,217
Tupelo, MS 11,017	Birmingham, AL 13,896	Montgomery, AL 10,085	Mobile, AL 14,738
Huntsville, AL 14,415	Tuscaloosa, AL 15,264	Hoover, AL 11,572	Dothan, AL 15,459
Decatur, AL 10,405	Auburn, AL 13,619	Gadsden, AL 10,265	Houston, TX 14,804
Austin, TX 15,978	Dallas, TX 18,103	San Antonio, TX 15,414	

6. Case Study

6.1 Data Description (Transportation Cost)

$$v_{kj}(\omega) = LH_k(\omega) \cdot vb \cdot d_{kj}$$

- $v_{kj}(\omega)$: Unit Transportation Cost for one evacuee from origin *k* to shelter *j*
- $LH_k(\omega)$: Scenario based weight
- vb: $ per evacuee per mile
- d_{kj}: Miles between origin *k* and destination *j*

Table 4 $LH_k(\omega)$ Values When a Category *t* Hurricane Landfalls 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)

,

6. Case Study

6.1 Data Description (Resources)

Table 5 Available Resources at Distribution Centers, a_{ir}

Distribution Center	Resource 1	Resource 2	Resource 3	Resource 4	Resource 5
Shreveport,LA	225,256	228,134	217,613	215,397	228,707
Baton Rouge,LA	207,045	217,146	204,282	222,609	214,199
Jackson,MS	224,312	209,614	213,999	216,399	227,476
Hattiesburg,MS	223,112	209,816	230,161	212,570	229,716
Birmingham,AL	214,038	219,692	211,080	215,177	209,016
Montgomery,AL	206,149	205,763	207,242	232,612	220,534
Dallas, TX	210,505	220,394	220,399	207,767	201,767

Table 6 Unit Transportation Cost, Surplus Cost, and Shortage Cost for Resources

	Resource Type				
	1	2	3	4	5
Unit Transportation Cost (rvb_r) ($ per mile per unit)	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

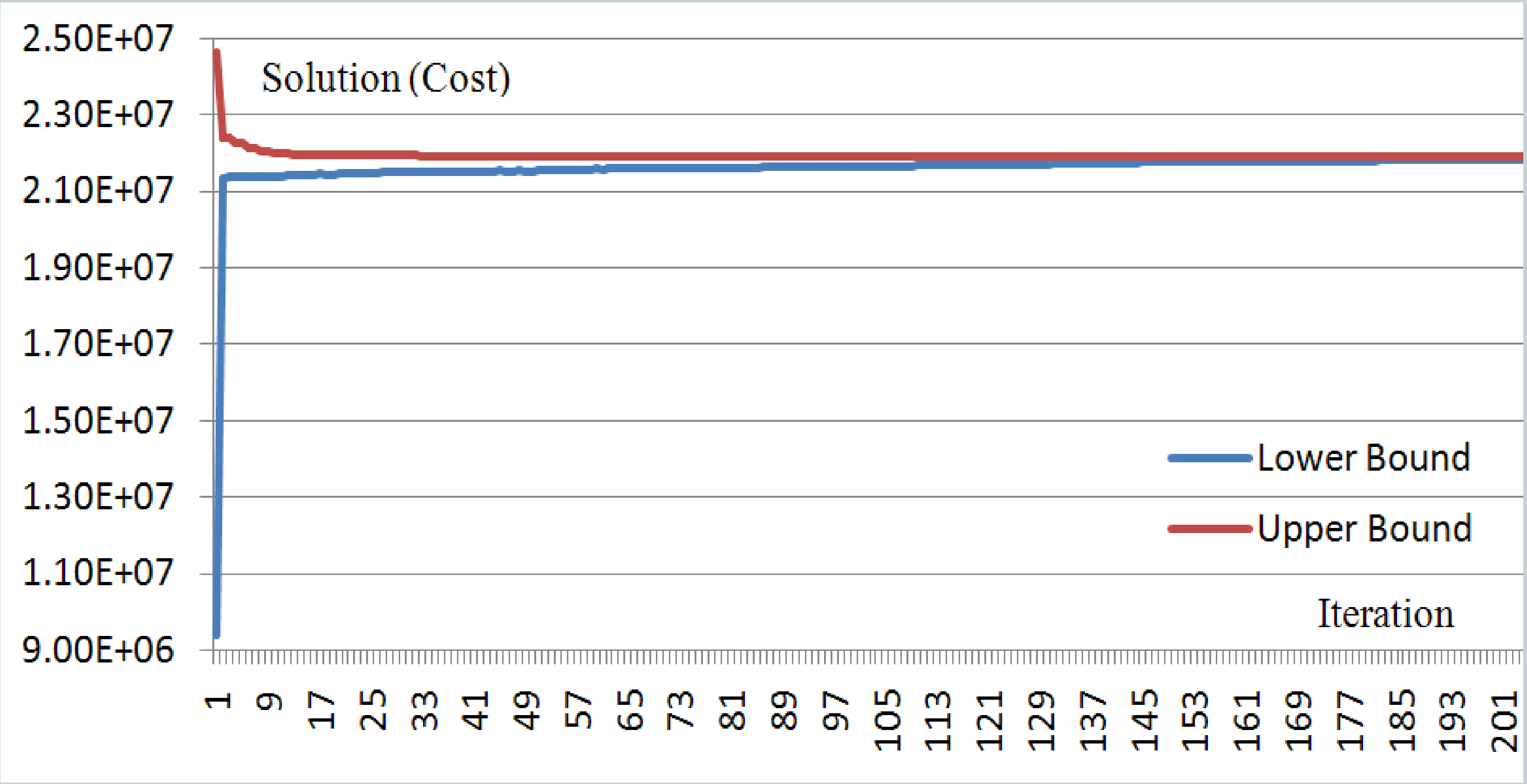
6. Case Study

6.2 Results and Analyses

- Problem Size
  - 57 existing permanent shelters, 26 potential shelters, 31 temporary shelters, 7 distribution centers, 5 types of emergency resource, 19 hurricane affected areas, and 45 evacuation scenarios
- Hardware
  - Dell desktop with Intel (R) Core (TM)2 CPU, 6600 @ 2.40 GHz and 2.00GB of RAM
- Software
  - Microsoft C++ calling the optimization solver of CPLEX 9.0
- Computational results
  - Optimal solution of $21,824,600 after 206 iterations and 3,509 seconds

6. Case Study

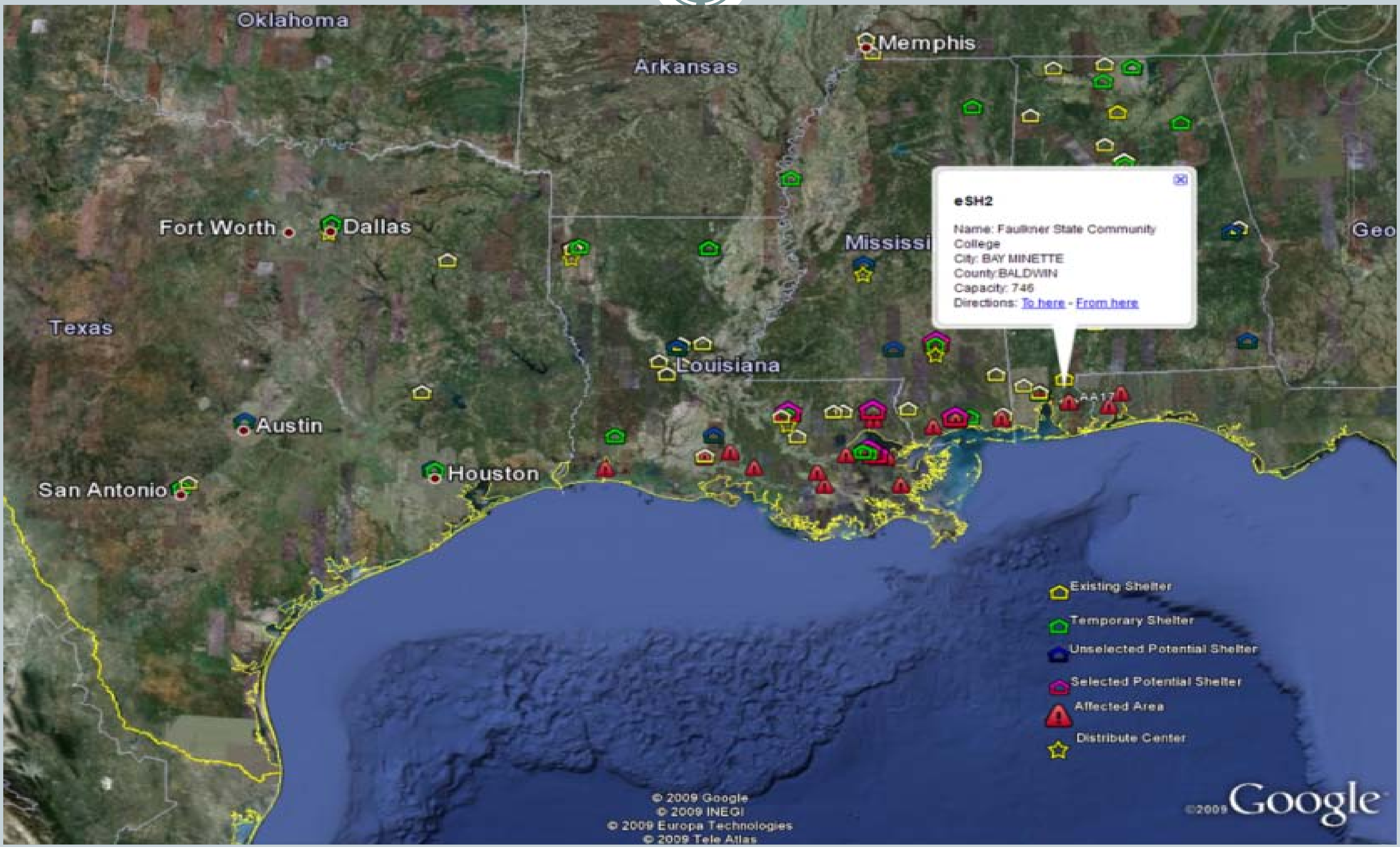
6.2 Results and Analyses



Convergence of The L-shaped Algorithm in Solving SNPOP

6. Case Study

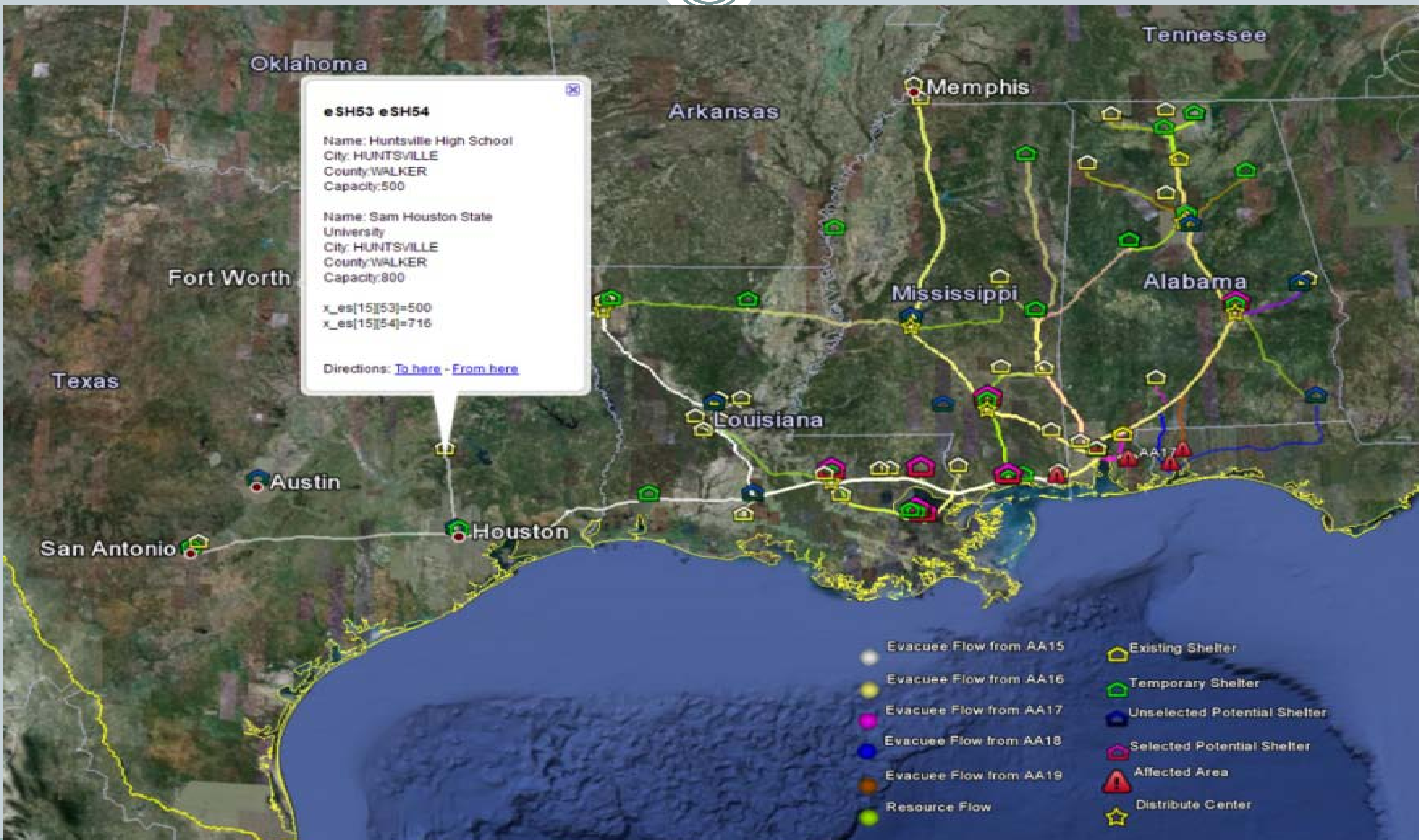
6.2 Results and Analyses (Preparedness)



Distribution of Shelters, Affected Areas, and Distribution Centers

6. Case Study

6.2 Results and Analyses (Response)



One Scenario Evacuation Process

7. Conclusion

- A two-stage, stochastic, mixed integer, sheltering network model is developed
  - Network design in the preparedness
  - Operations under all scenarios in the response
  - Considering both evacuee and resource flows
- The case study verified that the L-shaped method could solve a large scale sheltering network planning and operation problem by using a reasonable amount of time.