Spring 2015

Multiple-Objective Analysis of Integrated Relief Distribution and Network Restoration in Post-Disaster Humanitarian Logistics - Hazus based South Carolina (SC) Case Study

Kasin Ransikarbum
Clemson University

Scott J. Mason
Clemson University

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Kasin Ransikarbum, Scott J. Mason

Department of Industrial Engineering, Clemson University, Clemson, SC 29634, USA

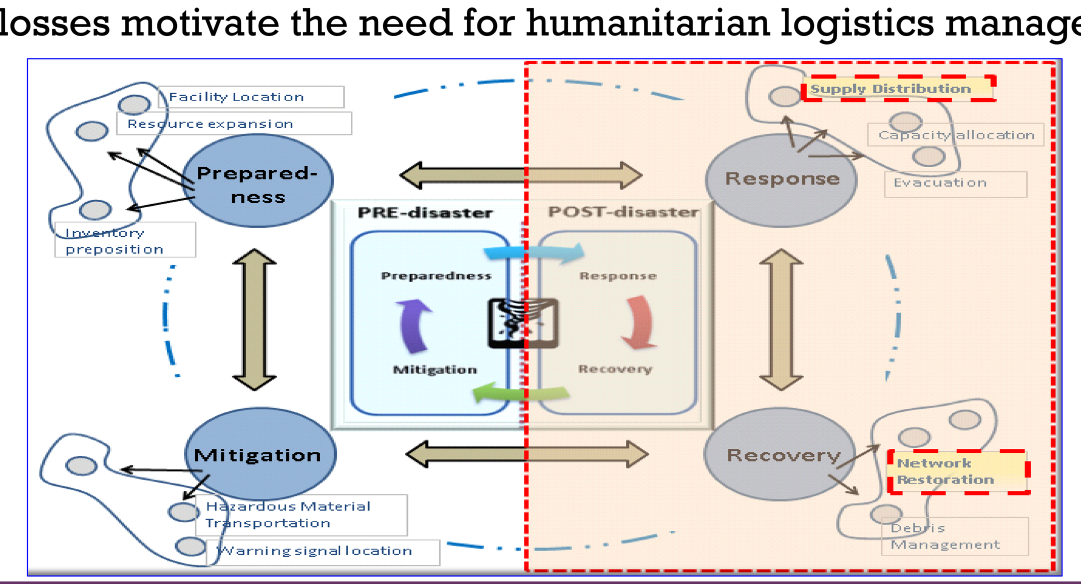
E-mail: kransik@clemson.edu, mason@clemson.edu

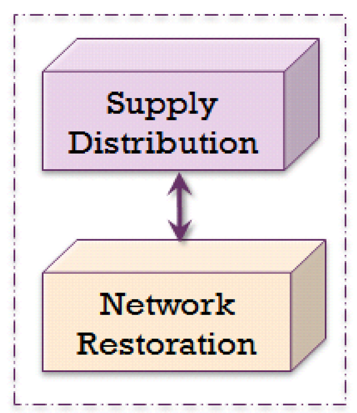
1. ABSTRACT

While several works exist in the pre-disaster operations, there is a clear need for research in post-disaster operations. The poster shows the Multiple-Objective Integrated Response and Recovery (MOIRR) model, which provides an equity- or fairness-based solution for constrained capacity, budget, and resource problems in post-disaster logistics management. Further, a designed experiment for this NP-hard problem is conducted to analyze important aspects of the integrated problem for both small- and large-sized networks: full vs. partial restoration and pooled vs. separate budgeting approaches. Finally, the model is applied to a Hazus-generated regional case study in South Carolina (SC) based on an earthquake scenario and efficient Pareto frontiers are generated to understand the trade-off between the objectives of interest.

2. INTRODUCTION

- The humanitarian logistics literature can be categorized into the four phases of the disaster management cycle related to pre- and post-disaster operations: 1) Mitigation, 2) Preparedness, 3) Response, and 4) Recovery.
- According to the World Disaster Report (2012), 6925 disasters took place between 2002 and 2011. More than 1.2 million casualties, over 2.6 billion affected people, and an estimated \$1.46 trillion in economic damage are reported. These significant losses motivate the need for humanitarian logistics management.





3. MOIRR MODEL AND COMPLEXITY CLASS

- We model the multiple-objective, mixed integer linear programming (MILP) model, which is intended to provide decision-makers with a set of strategic restoration plans for disrupted nodes and arcs in a network such that relief items can be equitably supplied to those in need.

Decision variables

$X_{i,j}$	Commodity flow integer variable for supplies through arc $(i, j) \in A$
K_i	Binary variable to restore disrupted supply port node $i \in S^D$
L_i	Binary variable to restore disrupted relief warehouse node $i \in T^D$
$M_{i,j}$	Binary variable to restore disrupted arc between port and warehouse $(i, j) \in \Lambda^D$
$N_{i,j}$	Binary variable to restore disrupted arc between relief warehouse and demand/beneficiary $(i, j) \in \Pi^D$
R_i	Units of unsatisfied unit variable for each demand node $i \in D$
V	Minimum percentage of satisfied demand
Y_i^S	Binary variable for set-up cost to restore disrupted supply port $i \in S^D$
Y_i^T	Binary variable for set-up cost to restore disrupted warehouse $i \in T^D$
$Y_{i,j}^{ST}$	Binary variable for set-up cost to restore disrupted arc between supply port and warehouse $(i, j) \in \Lambda^D$
$Y_{i,j}^{TD}$	Binary variable for setup cost to restore disrupted arc between relief warehouse and demand $(i, j) \in \Pi^D$

The first objective function in the model is to maximise equity or fairness modelled using maximin approach. This can be modelled as a linear programme to compute the minimum percentage of satisfied demand.

$$\text{Maximise } V \tag{1}$$

$$\text{Subject to} \quad V \le \left(\sum_{i \in T} \frac{X_{i,j}}{d_j} \right) 100; \quad \forall j \in D \tag{2}$$

The second objective is to minimise total unsatisfied demand. It can be defined as the sum of unsatisfied units across all demand/beneficiary nodes.

$$\text{Minimise } \left(\sum_{i \in D} R_i \right) \tag{3}$$

The third objective is to minimise the total network cost calculated as the funds spent to restore disrupted nodes, restore disrupted arcs and transport supply units based on origin-destination (O-D) pair information.

$$\text{Minimise } \begin{array}{l} \left(\sum_{i \in S^D} \eta_i^S K_i\right) + \left(\sum_{i \in T^D} \eta_i^T L_i\right) + \left(\sum_{i \in S^D} v^S Y_i^S\right) + \left(\sum_{i \in T^D} v^T Y_i^T\right) + \ldots \\ \left(\sum_{(i,j) \in \Lambda^D} \lambda_{i,j}^{ST} M_{i,j}\right) + \left(\sum_{(i,j) \in \Pi^D} \lambda_{i,j}^{TD} N_{i,j}\right) + \left(\sum_{(i,j) \in \Lambda^D} \omega^{ST} Y_{i,j}^{ST}\right) + \left(\sum_{(i,j) \in \Pi^D} \omega^{TD} Y_{i,j}^{TD}\right) + \ldots \\ \left(\sum_{(i,j) \in A} c_{i,j} d_{i,j}^{OD} X_{i,j}\right) \end{array} \tag{4}$$

- Objective functions (1), (3) and (4) can be normalized using a linear normalization technique to allow inter-criterion comparison. This technique converts objectives to a range between 0 and 1 based on ideal and anti-ideal solutions. Then, the weighted objective (non-preemptive) method can be applied.
- We can use a reduction technique to show that the MOIRR model reduces to the maximum concurrent flow problem (MCFP) and the multi-commodity integral flow problem (MIFP), which is known to be NP-complete.

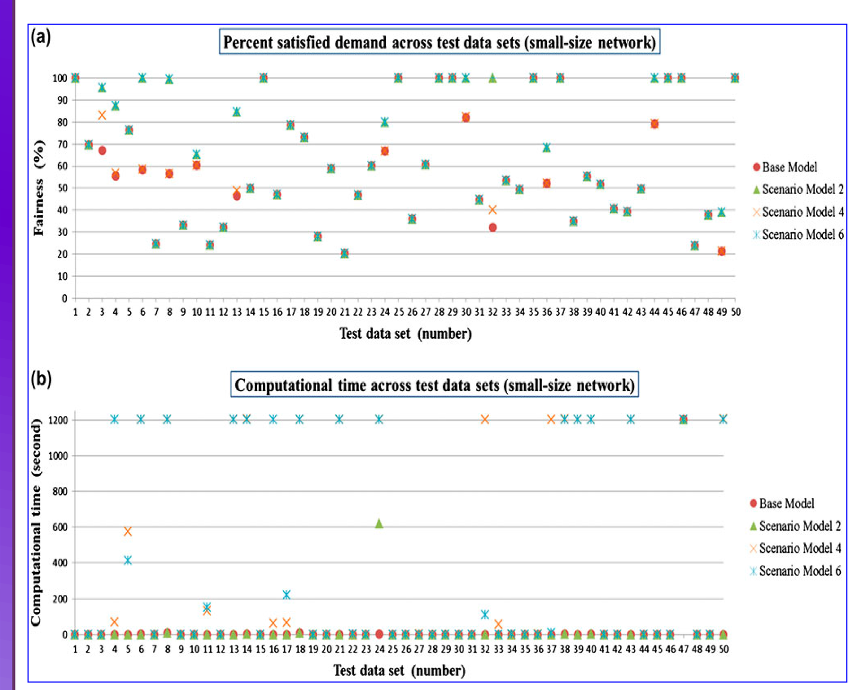
4. EXPERIMENTATION

- In order to gain managerial insights into significant model factors, we conduct a full factorial experimental design on three factors at two levels each: restoration type (full and partial), budget spending approach (pooled and separate) and network size (small and large).
- The MOIRR model is modelled in AMPL and analyzed using CPLEX solver.
- 50 test data-sets with different levels of disruption are randomly generated to verify and validate model functionality.

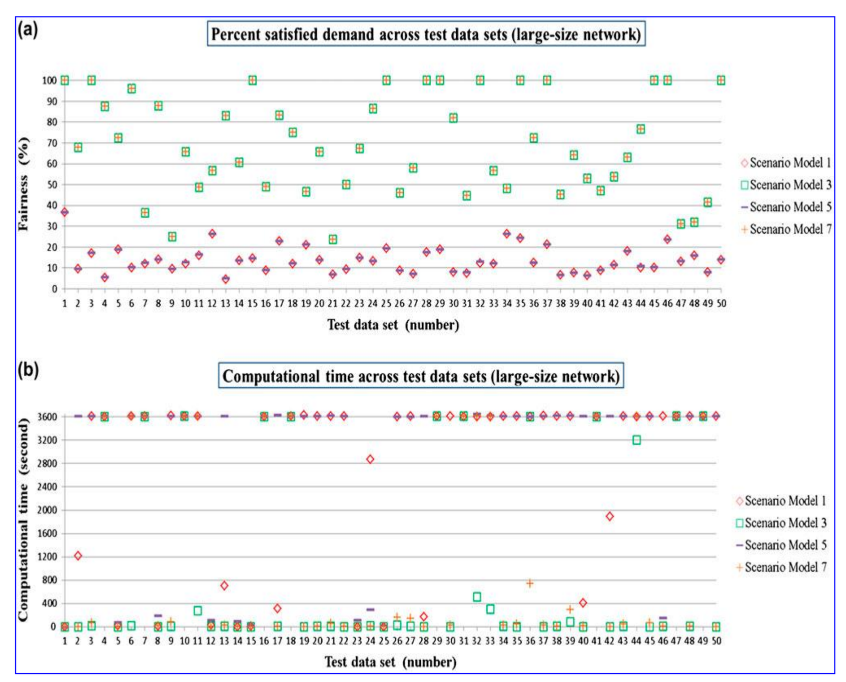
	Restoration		Budgeting		Network size	
Scenario number	Full	Partial	Separate	Pooled	Small	Large
Base scenario	✓		✓		✓	
Scenario 1	✓		✓			✓
Scenario 2	✓			✓	✓	
Scenario 3	✓			✓		✓
Scenario 4		✓	✓		✓	
Scenario 5		✓	✓			✓
Scenario 6		✓		✓	✓	
Scenario 7		✓		✓		✓

5. INITIAL RESULTS

- Small-size disrupted network: The percent of satisfied demand (fairness) fluctuates across these data-sets due to the randomness of network disruption. In terms of computation time, partial restoration-based models (scenarios 4 and 6) require higher computational time. Intuitively, this trade-off exists as more variables are required in the partial restoration scenarios.



(Small-sized network case)

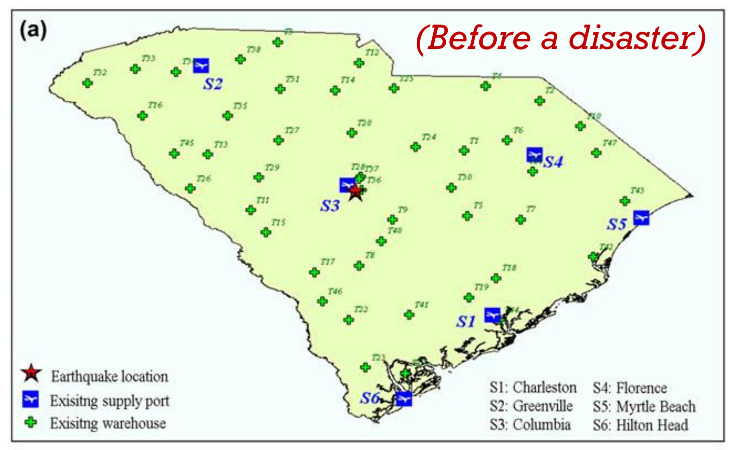


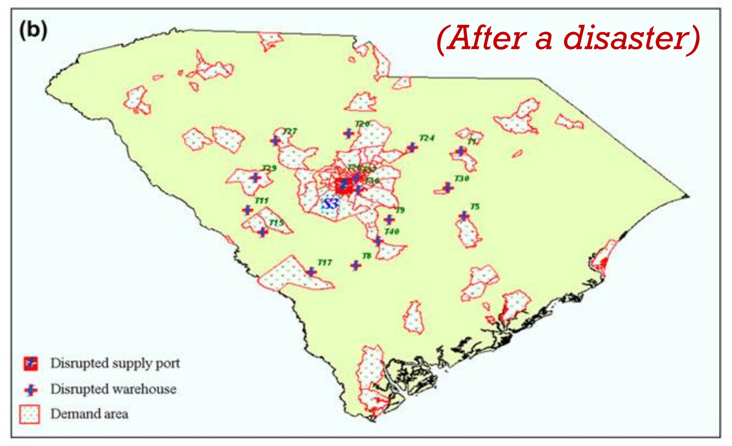
(Large-sized network case)

- Large-size disrupted network: It is clear that scenarios 3 and 7 that use pooled budgeting provide a much higher percent demand satisfaction than do scenarios 1 and 5 that employ separate budgeting. The pooled budget approach provides flexibility across organizations, given that budget parameters are limited. Further, computation time increases with problem size as expected due to the NP-hard complexity of the MOIRR model.

6. HAZUS METHODOLOGY

- The Federal Emergency Management Agency (FEMA) developed the Hazards US Multi-Hazard ('Hazus') tool; a geographic information system(GIS)-based natural hazard loss estimation software package that can estimate potential building and infrastructure losses resulting from catastrophic events.

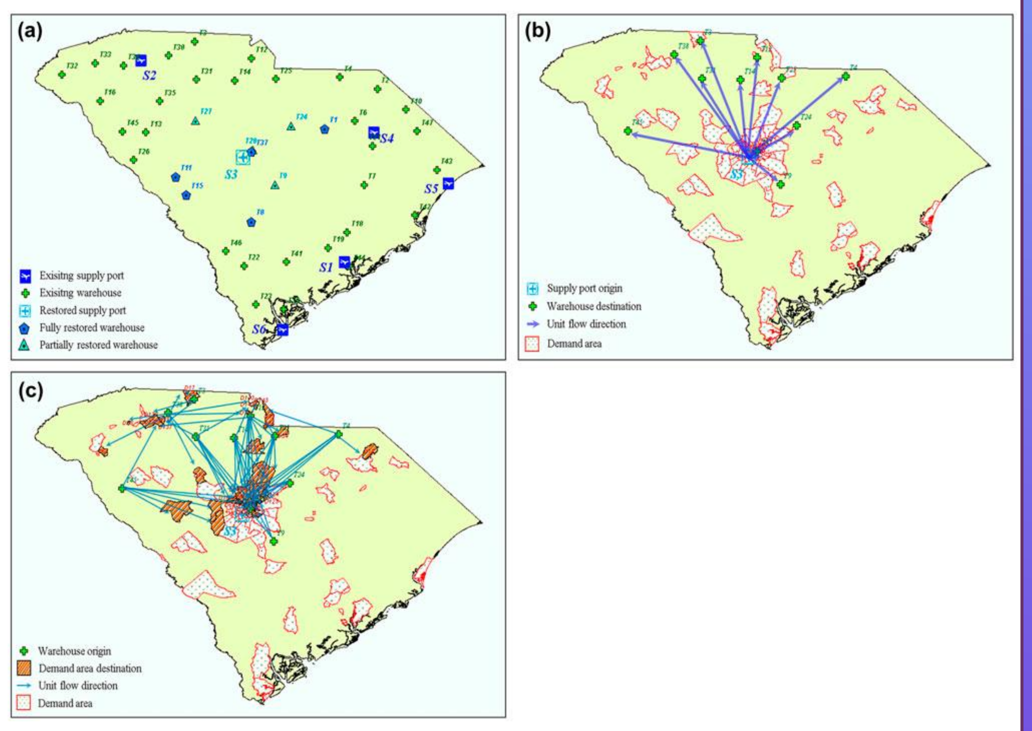




- Given a 9.0 magnitude earthquake in the Columbia, SC metropolitan area, Hazus calculates its output in a risk evaluation module and the resulting Hazus loss data are then used as input to the MOIRR model.
- Six major SC airports are chosen as relief supply points: 1) Charleston, 2) Columbia, 3) Florence, 4) Greenville, 5) Hilton Head, and 6) Myrtle Beach.
- One disrupted relief supply point, 16 disrupted warehouses and 143 demand census tracks were affected by the earthquake.

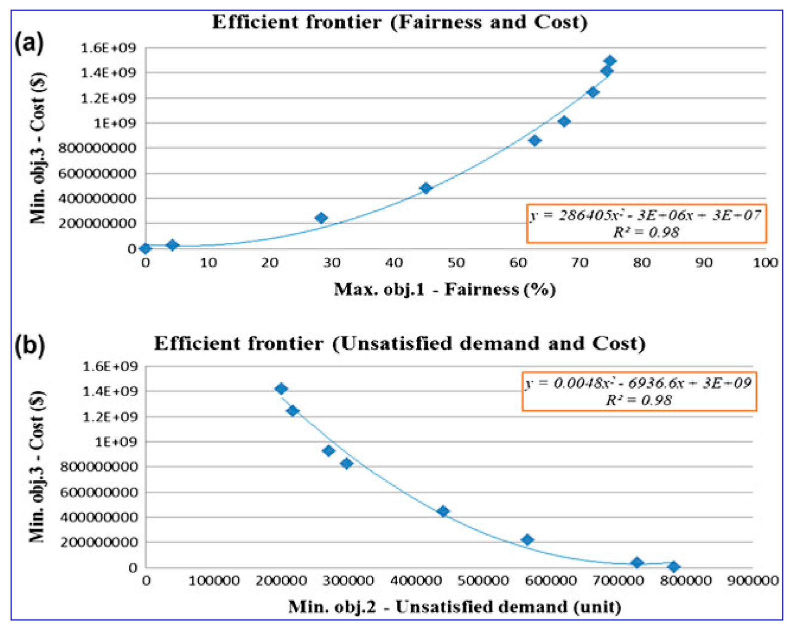
7. HAZUS RESULTS

- The Figure shows MOIRR model output for restoration and supply flow decisions.
- (a) five existing and one restored relief port, as well as 31 existing, five fully restored and four partially-restored relief warehouses.
- (b) example of flow decisions from the restored Columbia supply port to its relief warehouses.
- (c) example of flow decisions to associated demand points.



8. EFFICIENT (PARETO) FRONTIER ANALYSIS

- Solution trade-offs are developed for two different pairs of objectives: (a) Pair 1 (fairness vs. cost) and (b) Pair 2 (unsatisfied demand vs. cost).
- (a) when more weight is given to the fairness (e.g., w1:w3 = 0.7: 0.3), the objective values for fairness and total cost are 72.2% and \$ 1.25 billion, respectively. However, when more weight is given to the cost (e.g., w1:w3 = 0.3 :0.7), the corresponding objective values are 28.4% demand satisfaction and \$ 0.24 billion for total cost, respectively.
- (b) Pair 2 study can be interpreted in a similar way.
- By using a polynomial trend line analysis, a decision-maker can quickly examine how different objective weights affect important trade-offs.



$$\text{Maximise} \quad w_1 \left(\frac{(1) - L_1^*}{H_1^* - L_1^*} \right) + w_3 \left(\frac{L_3^* - (4)}{L_3^* - H_3^*} \right)$$

$$\text{Maximise} \quad w_2 \left(\frac{L_2^* - (3)}{H_2^* - L_2^*} \right) + w_3 \left(\frac{L_3^* - (4)}{L_3^* - H_3^*} \right)$$

9. CONCLUSION AND FUTURE WORK

- We develop a multiple objective model that integrates the supply distribution problem (response) with the restoration problem (recovery) operations.
- As performance measures in relief operations are not only cost-based, we also consider an equity- or fairness-based solution approach.
- It is clear that partial restoration under pooled (coordinated) budgeting approach provides flexibility when budgets are limited in a highly disrupted network.
- The MOIRR model was applied to a South Carolina-based case study using loss data estimated from FEMA's GIS-based loss estimation software, Hazus.
- The efficient frontiers are developed to understand the trade-offs between the different objectives of interest.
- Future work includes a goal programming (GP) approach that yields a compromise solution and a multiple objective metaheuristic approach that provides practical, effective solutions to this NP-hard problem in a timely manner.

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