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A Dynamic Distribution Model for Hurricane Relief

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ABSTRACT

A disaster can be described as an unexpected event that causes economic damage, destruction, and human suffering. Numerous studies have addressed the importance of Decision Making for Emergency Management (DMEM) tools. This paper focuses on one aspect of DMEM, namely how to effectively deliver survival goods to victims immediately after a hurricane hits a populated area. The first decision in designing a distribution network is where to locate the supply nodes. Although many models are found in the literature that deal with the location of distribution sites, only a small number of these address the problem of locating these sites when a disaster will hit an area. In this study, a dynamic distribution model to locate facilities and distribute commodities during the response phase of a hurricane disaster is presented. The problem is modeled as a two stage network, where commodities are transported from State Staging Areas (SSAs) to Points of Distribution (PODs), and subsequently, dispensed to victims. The approach taken is that of a gradual activation of locations, with the incorporation of risks and demand uncertainties.

Keywords: Hurricane relief, distribution, emergency management.

1. INTRODUCTION

An emergency is a deviation from a planned course of events that endangers people, properties, or the environment. An emergency becomes a disaster when exceeds the capability of local resources to manage it or contain it (Johnson, 2000). The discipline of emergency management has emerged from the need of governments and organizations to better prepare for and deal with emergencies and disasters.

Numerous studies have addressed the importance of having decision making tools for emergency management, especially because we have seen over the past two decades natural disasters that have caused thousands of deaths around the world.

In 2004, four major hurricanes caused flooding and hundreds of tornadoes in the United States. In September 2004, 247 tornadoes were reported, breaking the previous record of 139 set in 1967 (NOAA, 2004), an increase of 77%. $1.8 billion in government funds were budgeted all for disaster relief in 2004, while over 1.1 million people registered just for hurricane related assistance (FEMA, 2004). The Department of Homeland Security, through the Federal Emergency Management Agency (FEMA), is responsible for responding to large-scale emergencies. In 2004, they supplied $2.25 billions for disaster relief and 15,560 federal workers to assist people impacted by disasters (FEMA, 2004).

In 2005, two major hurricanes hit the United States. Hurricane Katrina (August) struck parts of Florida and Louisiana, becoming one of the most devastating natural disasters in United States history. Four weeks later, Hurricane Rita (September) affected Florida resulting in over $1 billion in damages. Rita was followed by Wilma (October), which affected Florida worse than Rita. As of November 30, 2005, $32 billion of the Disaster Relief Funds were used to provide emergency assistance to victims, communities, and states affected by hurricanes and other declared major disasters and emergencies (Belasco 2005).

Providing adequate support to communities is a complex problem because of the randomness of the factors to consider. The number of possible scenarios increases considerably with the size of the geographical area, size of population, and intensity of the hurricane. Emergency managers are expected to activate and allocate the resources required for the emergency, but they may not have the analysis capabilities to determine how many resources they need.

This paper addresses the problem of how to efficiently and effectively deliver basic relief goods to victims of a hurricane disaster. Despite the advances in information management and systems modeling, we still lack adequate means to support emergency decision makers and managers as Hurricane Katrina taught us.

The emergency response problem is both complex and huge. This paper looks into the logistics aspects of the problem, in an attempt to develop a hurricane relief distribution network model that is dynamic. Specifically, this effort has focused on the distribution of relief commodities because it is one of the 17 critical areas identified by the US Government after Hurricane Katrina [1].

1.2 Emergency Management

In the United States, emergency management has four phases (Figure 1): mitigation, preparedness, response, and recovery (Waugh, 2000; Green, 2002, FEMA 2003). *Mitigation* occurs before the disaster, and it includes activities to prevent an emergency, to reduce the chance of it happening, or to reduce the damaging effects of it. *Preparedness* also takes place before the disaster, and it includes activities to prepare the community to respond when a disaster occurs. *Response* occurs both before and immediately after a disaster, overlapping to some degree with the Preparedness phase. *Recovery* may occur over a period of months or years, depending on the severity of the emergency or disaster, and it involves the actions taken for the long term after the immediate impact of the disaster has passed.

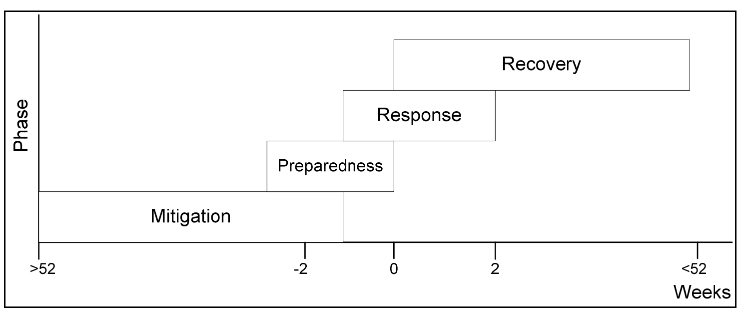

Figure 1: Timeline of Emergency Management Phases

This paper has focused on analysis and planning methods needed for the response phase of hurricane emergencies. The relief distribution problem can be broken down into four sub-problems: 1) Location, 2) Commodity Allocation, 3) Resource allocation and 4) Vehicle Routing. All four problems have been studied for situations where much control and stability exits, e.g. manufacturing and service logistics. For the case of a hurricane emergency, the results of previous works need to be enhanced to allow dynamic re-evaluation, and they must cohesively integrate to support decision makers.

2. LITERATURE REVIEW

More than two dozen articles were published between 1969 and 1989 that described models for emergency response operations, including firefighting, ambulance, and police operations [2]. However, very few articles have been published since then. The number of publications have decreased because the models published seemed to address the basic problems faced in emergency systems [2].

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Although many models are found in the literature that deal with the location of distribution sites, only a small number of these address the problem of locating these sites when a disaster will hit an area. In addition, the resulting models fail to capture the dynamics of emergency response. For instance, [3] limited their models to determine the number of facilities to open to minimize the distance traveled by the users to reach the facilities. [4] dealt with the location of a single facility over a region in r time periods, whereas emergency response needs multiple facilities.

[4], [5], [6], [7], and [8] are just some of the authors who have developed location models with the objective of minimizing total costs. Minimizing costs is always desirable; however, in the case of emergency response it is more important to minimize the unmet demand, to minimize the risk to the selected sites and the distance to the distribution sites.

More in tune with the needs of emergency response are the works by [9], [7], and [8], specially the one by [8]. [8] formulated a multi-commodity model to determine the location of the facilities such that the cost of locating a facility at a given site is minimized. Along the same line is [10] who developed a decision model that identifies the minimum number of locations to open and their possible sites. The purpose of the model is to locate sites to store critical documents and equipment of a company when a disaster hits.

Recently, [11] modeled the location problem using goal programming for an earthquake scenario. Although the objectives were described, the target value for each of the objectives was not specified. But it is on of the few works that deal with multiple objectives as needed for emergency response, such as minimization of time to transport goods, the risk of opening facilities, unsatisfied demand and the cost of opening the facilities.

Once the location of the points of distribution has been decided, the distribution of commodities should be initiated. Like in the case of the location problem, only a handful of efforts have looked at the distribution and clustering of goods for emergency response. Most of these efforts have treated the problem as a deterministic one, or they have dealt only with one or two commodities to allocate.

The past 10 years (1997-2007) have seen research that actually are more suited for emergency response as they deal with multiple commodities ([12] and [13]); however, most model parameters are assumed deterministic. [12] developed a mathematical model that integrates the multi period multi-commodity network flow problem with the multi period vehicle routing problem (VRP) to determine the amount of commodities that need to be sent to the demand nodes.

Later on, [13] improved [12] model by including the amount of wounded people as part of the decision variables. The model minimizes the amount of unsatisfied demand (in terms of the number of persons who do not get commodities), and the number of wounded people not served at a node at time t.

Few papers have addressed the problem of distributing relief supplies as a stochastic problem. That is the case of [14] that proposed a two stage stochastic model to transport the relief aid to the affected areas after an earthquake. In the model, the mobilization of resources is treated as a random variable, as well as the amount of commodities needed in the affected nodes. This model was developed specifically for Earthquake scenarios.

Currently, there is no tool that can help emergency managers decide where to locate the PODs to distribute commodities to the population, or the amount of commodities that each location should receive. The DSS tool needs to have the following characteristics:

1. Deal with uncertainties: demand, supply, damages to roads.
2. Provide capability to dynamically manage resources according to current weather conditions.

3. MODEL STRUCTURE AND FORMULATION

3.1 Model Description

When a Hurricane hits, emergency managers are expected to have a response plan based on the available information. Unlike with earthquakes and terrorist attacks, a hurricane response plan can be prepared ahead of time, since a hurricane is predicted at least five days before it makes landfall [15]. Enough time is given to prepare a well organized response plan for the location and distribution of commodities.

The objective of the location model is to establish a set of facilities so that they can serve a set of demand points, such that the amount of demand nodes covered is maximized. The model is a multi-level network that consists of 2 echelons: SSA – PODs, which are the last two echelons of the Logistics Supply Chain (LSC) for emergency response delineated by FEMA (Figure 2) (FEMA, 2006).

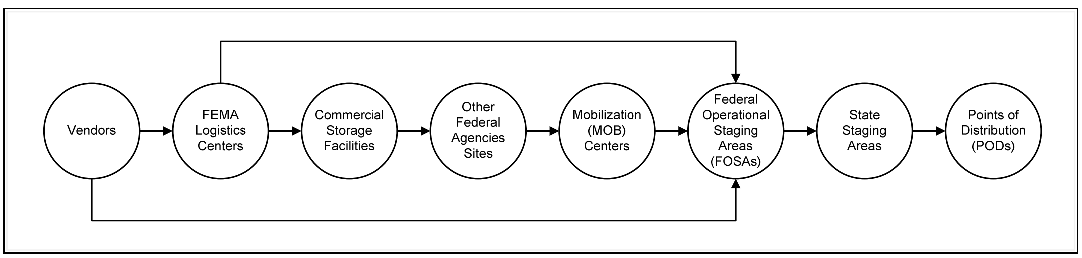

Figure 2: Supply Chain to provide commodities to disaster victims

The outcome of the dynamic distribution model is a plan to locate a set of Supply Nodes $\overrightarrow{NS}$ (SSAs) and a set of Demand Nodes $\overrightarrow{ND}$ (PODS). The model also attempts to develop a delivery plan to transport a set of commodities *K* from the $\overrightarrow{NS}$ (SSAs) to the $\overrightarrow{ND}$ (PODs) over an undirected graph *G(N,A)* that contains a maximum of $N+M$ nodes and $M \text{ x } N \text{ x } K$ arcs. Demands at each POD are different for different commodities, at different points in time (d_{ikt}).

The network contains the supply nodes $\overrightarrow{NS}$ and the demand nodes $\overrightarrow{ND}$. In the $\overrightarrow{NS}$ (State Staging Areas) commodities are pre-positioned for deployment, so a specific amount of commodities are available at the $\overrightarrow{NS}$ at $t=1$. The amount of commodities of type K sent from node j to node p is denoted by a_{jpk}. Each source node $\overrightarrow{NS}$ has $M \text{ x } K$ outgoing arcs, corresponding to each T period.

3.2 MODEL FORMULATION

The decision is how many facilities to open, and whether to activate a pre-defined facility or not as a SSA and POD. The problem is formulated as a multi-objective programming model. The decision of activating the locations is taken according to the expected values of two objectives:

- Maximize the total satisfied demand
- Minimize the total expected weighted distance traveled by the victims to the nearest POD.

4.1 NOMENCLATURE

The nomenclature used in the mathematical model is the following:
Index Sets:

I = Number of sub areas hit by the disaster
N = Number of supply nodes (SSAs)
M = Number of Demand Nodes (PODs)
T = Number of periods in planning horizon
K = Number of commodities to distribute
S = Number of possible scenarios
$\overrightarrow{NS}$ = $\{1,2,...,N\}$: Set of Supply Nodes (SSAs)
$\overrightarrow{ND}$ = $\{1,2,...,M\}$: Set of Demand Nodes (PODs)
$\vec{A}$ = $\{1,2,...,I\}$: Set of Areas that will be hit by the disaster
d^i_{pkt} = Expected demand of commodity k at node p at time t
W_{ipt} = $\begin{cases} 1, & \text{if POD p in area i is affected at time t} \\ 0, & \text{otherwise} \end{cases}$
V_{it} = $\begin{cases} 1, & \text{if Area i is affected at time t} \\ 0, & \text{otherwise} \end{cases}$
C^i_p = Storage capacity of POD p in area i
I^i_{pt} = Final Inventory at POD p in area i at time t
p(s) = Probability that scenario s takes place
$p(r/s)$ = Probability of risk of site p given scenario s
D_{jp} = Distance from Supply node j to demand node p
E^i_p = Average distance from Area i to POD p
MD_{jp} = Maximum distance allowable between a SSA and a POD
r_{it} = Expected risk of POD p at time t
R = Maximum global amount of risk allowable for potential PODs

Decision Variables

Z^i_{pjt} = $\begin{cases} 1, & \text{if POD p in area i is served by SSA j at time t} \\ 0, & \text{otherwise} \end{cases}$
X^i_{jt} = $\begin{cases} 1, & \text{if SSA j in area i opens at time t} \\ 0, & \text{otherwise} \end{cases}$
Y^i_{pt} = $\begin{cases} 1, & \text{if POD p in area i opens at time t} \\ 0, & \text{otherwise} \end{cases}$
R^i_{pt} = $\begin{cases} 1, & \text{if Region i es served by PODj at time t} \\ 0, & \text{otherwise} \end{cases}$
a_{jpkt} = Amount of commodity k sent from SSA j to POD p at time t .

Without loss of generality, we can say that the amount of products demanded by a region is the product demanded by all the PODs that are in that region.

Goal 1: Satisfied Demand

$$\sum_{t\in T}\sum_{i\in I}\sum_{k\in K}\left[\left(\frac{A_{jpkt}\cdot Y_{ipt}\cdot X_{ipt}}{\sum_{j\in J} Demand_{kj}}\right)\right] \leq \text{ Target Level}$$

Goal 2: Distance Traveled

$$\sum\sum Y_{jt}^{i} E_{p}^{i} \leq \text{ Target Level}$$

The model minimizes the deviations of our two goals.

$$Min \quad G1^{+} + G2^{+}$$

s.t.

$$Z_{pj}^{i} - X_{j}^{i} \leq 0 \qquad \forall i, j, p \tag{1}$$

$$X_{j}^{i} - V^{i} \leq 0 \qquad \forall i, j \tag{2}$$

$$\sum_{j\in J} X_{j}^{i} C_{j}^{i} \geq d^{i} V^{i}, \qquad \forall i \tag{3}$$

$$\sum_{p\in P} Y_{p}^{i} C_{p}^{i} \geq d^{i} V^{i} \qquad \forall i \tag{4}$$

$$\sum_{j\in J} Z_{jp}^{i} \cdot Y_{p}^{i} \leq 1 \qquad \forall \quad p, \quad \forall t \tag{5}$$

$$R_{p}^{i} - Y_{p}^{i} = 0 \qquad \forall i, p \tag{6}$$

$$r_{i} \cdot Y_{pt}^{i} \leq R \qquad \forall \quad i \tag{7}$$

$$E_{ip}(Y_{pt}^{i}) \leq MD \qquad \forall \quad i, j \tag{8}$$

$$a_{jp} \geq d_{pk}(Z_{pjt}^{t}) \quad \forall \quad i, j, k \tag{9}$$

$$a_{jp} \leq c_{pk}(Z_{pjt}^{i}) \quad \forall \quad i, j, k \tag{10}$$

$$Z_{jpt}^{i} \leq (Y_{pt}^{i}) \quad \forall \quad p, j, k \tag{11}$$

(1) If a SSA j in area i is not opened, then that SSAs can not provide commodities to the PODs. Otherwise, if the SSA j is opened, then POD p may or may not be served by the SSA j.

(2) If an Area i is not impacted by the hurricane, then the SSAs in that area will not open. Otherwise, if the Area i is affected, then the SSA j may or may not open.

(3) The capacities of the opened SSAs should be greater than the demand of the population if the area is hit by the disaster.

(4) The capacities of the opened PODs should be greater than the demand of the population if the area is hit by the disaster.

(5) A POD can only be served by one SSA. Further, that SSA should belong to the same area as the POD.

(6) The expected risk associated with an opened facility should be less than a target level pre-established.

(7) The expected risk associated with an opened facility should be less than a target level pre-established.

(8) The distance traveled by victims to the nearest POD should be less than or equal to maximum distance allowed by the decision makers.

(9) The amount of commodity k that can be sent from a SSA j to a POD p should be greater than the demand.

(10) The amount that can be sent from the SSA to a POD should be less than the storage capacity of the POD.

(11) A SSA can not supply a POD that is not open.

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