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Inventory planning and coordination in disaster relief efforts

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ABSTRACT

This research proposes a stochastic programming model to determine how supplies should be positioned and distributed among a network of cooperative warehouses. The model incorporates constraints that enforce equity in service while also considering traffic congestion resulting from possible evacuation behavior and time constraints for providing effective response. We make use of short-term information (e.g., hurricane forecasts) to more effectively preposition supplies in preparation for their distribution at an operational level. Through an extensive computational study, we characterize the conditions under which prepositioning is beneficial, as well as discuss the relationship between inventory placement, capacity and coordination within the network.

1. Introduction

Coordinating emergency supplies during the aftermath of a disaster is one of the main challenges associated with immediate response efforts. Information about available resources is often unknown and contributions of suppliers can be unpredictable (Kovacs and Spens, 2007). Adding to the challenge is the fact that the disaster relief environment in large-scale, catastrophic events often involves many actors such as non-governmental organizations (e.g. Red Cross); various local, state, and federal government agencies (e.g. FEMA); faith based organizations (e.g. churches); and firms in the private sector (e.g. local grocers). Some organizations function autonomously providing specialized products (e.g. food, water) or services (e.g. medical assistance, sheltering.). Others work within a larger collaborative structure led by either the governmental authority of the affected area (NRF, 2008) or a coordinating agency such as the United Nations Joint Logistics Center (Kaatrud et al., 2003; Balcik et al., 2010).

Most scholars agree that coordination can improve effectiveness of initial response efforts (e.g. Stephenson, 2005; Van Wassenhove, 2006; Chandes and Pache, 2010; Balcik et al., 2010). However, coordination can also be quite challenging as evidenced by the Indian Ocean tsunami. The relief operation for this particular disaster was described as "chaotic" due to the large influx of new and inexperienced organizations and volunteers, an overwhelmed government, and an absence of regulatory measures to control and manage the entry of volunteers and goods (Van Wassenhove, 2006).

A number of quantitative models in the disaster relief literature have addressed issues related to inventory management such as inventory placement/prepositioning, determining quantities of relief supply to stock in advance of a disaster, and determining how the inventory should be distributed post-disaster. However, inventory coordination during disaster relief efforts has largely been unexplored. There is some evidence that inventory coordination in the form of sharing information and/or warehouse space occurs during disaster relief efforts (Balcik et al., 2010). For example, the UN Humanitarian Response Depot supports strategic stockpiling efforts of the UN, international, governmental and non-governmental relief organizations (www.hrdlab.eu). The state of Florida has a logistics warehouse to coordinate the efforts of state and federal responders (SLRC, 2012). However, many non-governmental organizations that participate in disaster relief have their own warehouse network where they stock supplies. For example, Feeding America, a non-profit hunger relief organization, has warehouses across the United States where they receive donated food. Some faith based organizations (e.g. Church World Service, United Methodist Committee on Relief) that participate in disaster relief activities through the Voluntary Organizations Against Disasters (VOAD) own warehouses that stock relief supplies. Coordination among these various participants requires accurate information as well as frequent communication regarding the availability of their resources. Better planning and information regarding disaster resources will help to eliminate redundancy, duplication of effort and potentially unused supply.

In this paper, we address inventory management decisions in the context of coordination. Specifically we consider the problem

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of prepositioning local and external supplies within a cooperative distribution network prior to an upcoming natural disaster, such as a hurricane. The term *local* refers to supplies that are stored close to the affected area and perhaps managed by a local governmental authority. *External supplies* refer to those goods available from an outside agency. We define a *cooperative distribution network* as a group of entities who normally act autonomously, but under severe disaster conditions, try to come together to provide assistance and aid to the affected population. We explore a specific coordination structure characterized by two parameters: reserve capacity (warehouse space) and inventory commitment (relief supplies) and identify conditions under which coordination and supply allocation decisions are beneficial. We take into consideration road congestion resulting from (i) pre-disaster evacuation activities and (ii) post-disaster road damage.

Prepositioning is not a new concept, as the military has used this for quite some time (Johnstone et al., 2004). However, it is becoming more widely studied and applied in the context of emergency response (e.g. Duran et al., 2011; Lodree and Taskin, 2009; Rawls and Turnquist, 2010). The majority of the research on prepositioning occurs at the strategic level addressing long-term supply network decisions such as where to establish supply locations, and how much material to stock there. The best location is weighed against disaster uncertainty (demand for resources) through the use of probability distributions that represent the likelihood of potential disaster scenarios. The majority of the data used to determine these probability distributions are historical in nature; that is they do not often incorporate information such as forecasted hurricane paths that affect the probability a particular site will be affected by a disaster. The model presented in this paper incorporates forecasted hurricane path and intensity to determine how best to preposition supplies in an established single commodity supply network where one or more of the nodes is in a high-risk path for a particular event. This situation could arise either when strategic prepositioning decisions have been made, or when an existing network is already used to service the community. Since the network under consideration already exists, the problem we consider makes no location decisions. We instead consider the relocation of supplies in advance of a disaster to minimize the possible destruction of those goods, and to aid the distribution of supplies to service those affected by the disaster after it occurs. In our context, relocation of supplies can be considered repositioning rather than prepositioning. However we adopt the term prepositioning as the supplies are positioned prior to the occurrence of the disaster event. We consider uncertainty in demand and available supply and use a stochastic linear programming model to determine the placement of supply within the network to minimize the number of people who cannot be served post-disaster. In addition, we address the uncertainty in the location of the disaster using short-term forecasts such as those available prior to hurricanes.

This paper makes the following contributions to the literature. The problem we consider is in the preparedness domain (vs. post-response). To the best of our knowledge, this is the first paper in the preparedness domain to consider inventory coordination in emergency planning. Secondly, we consider uncertain supply as well as uncertain demand. It should also be noted that the majority of papers consider historical information to determine where to preposition supplies. In contrast, we consider short-term forecasts to determine where to preposition supplies so as to prevent damage to supplies, while also considering timely service to those affected by the disaster. Lastly, we examine the impact of coordination in the network to provide improved response post-disaster. The coordination decisions considered determine (1) how much supply from external suppliers to preposition, (2) how much local (internal) supply to reposition, and (3) where the external/internal prepositioning activity should take place in the network. Since the first 72 h following a disaster are critical (Salmeron and Apte, 2010), coordination is characterized as a function of the response time and average fill rate. Lastly, we explore the impact of the coordination decisions from a cost and service perspective.

The remainder of the paper is organized as follows. In Section 2 a review of related literature is presented. The model and assumptions are presented in Section 3. Section 4 outlines the numerical study considered in this work, including the specific research questions that are addressed and assumptions made regarding the data used. Computational results are reported in Section 5, followed by concluding remarks in Section 6.

2. Literature review

Much of the prepositioning literature addresses stock levels for relief supplies, location of relief supplies, and/or distribution of relief supplies. Inventory stocking and location decisions are typically implemented in advance of the emergency event, and often reflect long term strategic resource allocation decisions. Distribution of relief supplies happen during the response phase after event demand has been realized and reflects short term resource allocation decisions. Several prepositioning models integrate both preparedness and response decisions using scenario-based approaches such as stochastic programming. The following discussion of the relevant prepositioning literature is classified by the preposition decision. Specific aspects of the model relating to supply and demand uncertainty and the planning horizon are highlighted, where applicable. Short term resource allocation models in the context of humanitarian relief are also discussed.

2.1. Location determination

Many of the location determination models used in the humanitarian relief context are modeled as extensions of the well known facility location models which are adapted to consider uncertainty in demand induced by disaster events. Jia et al. (2007) develop models to determine the location of medical services during large scale emergencies under various objectives: (i) maximize the demand covered by a certain number of facilities, (ii) minimize the demand weighted distance between the new facilities and the demand points, and (iii) minimize the maximum service distance. Both proactive (strategic) facility location decisions and reactive (short term) location decisions are considered. The proactive location case determines where facilities should be located for long term storage of medical supplies such that they can be delivered quickly to demand points, if a terrorist attack occurs. The reactive location case determines where staging centers should be positioned to receive and distribute medical supplies from strategic inventory stockpile locations. Uncertainty in demand is a function of the population covered by a demand point and the impact the attack scenario is likely to have on the demand point. Ukkusuri and Yushimito (2008) also model the supply prepositioning problem as a facility location problem, incorporating routing as well as location decisions. They consider a network location model where existing demand points are considered as candidate locations to preposition supplies, taking into account that possible disruptions in the transportation network can occur via node or link failures. The objective is to choose the locations and routes in such a way that the reliability of reaching a demand point is maximized. *Demand surge* and *supply quantities* are not considered in this model. Yi and Ozdamar (2007) also consider preposition location and routing decisions. They present a multi-period capacitated location-routing problem that incorporates multiple commodities, different categories