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Innovative Applications of O.R.

Location and capacity allocations decisions to mitigate the impacts of unexpected disasters

Jomon Aliyas Paul, Leo MacDonald*

Department of Economics, Finance and Quantitative Analysis, Coles College of Business, Kennesaw State University, 560 Parliament Garden Way, Kennesaw, GA 30144, United States

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ABSTRACT

This paper develops a stochastic modeling framework to determine the location and capacities of distribution centers for emergency stockpiles to improve preparedness in the event of a disaster for which there is little to no forewarning. The proposed framework is applicable to emergency planning that must incorporate multiple sources of uncertainty, including the timing and severity of a potential event, as well as the resulting impact, while taking into consideration both disaster and region specific characteristics. To demonstrate the modeling approach, we apply it to a region prone to earthquakes. The model incorporates various uncertainties such as facility damage and casualty losses, based upon their severity and remaining survivability time, as a function of the magnitude of the earthquake. Given the computational complexity of the problem of interest, we develop an evolutionary optimization heuristic aided by an innovative mixed integer programming model that generates time efficient high quality solutions. We demonstrate the effectiveness of the heuristic via a case study featuring the HAZUS-MH software from the Federal Emergency Management Agency (FEMA). Finally, given the uncertainty associated with the magnitude of the earthquake, we use a decision analysis approach to develop robust solutions while taking into account the geological characteristics of the region.

1. Introduction

Natural disasters have the potential to result in significant economic and societal losses. For instance, in 2012, natural disasters affected more than 100 million people, causing more than 900 deaths in 115 countries (CRED, 2013). The economic damages alone were estimated to be 113billion dollars. To complicate matters, these disasters often disrupt normal supply chains, making it challenging for treatment centers, such as hospitals, nursing homes and long-term care facilities, to obtain essential equipment, pharmaceuticals and other medical supplies. The resulting inability to provide the necessary care to those incapacitated as a result of the disaster could lead to long term health impacts and increased fatality rates. Therefore, the development of disaster preparedness and response plans that consider the public health consequences while incorporating the unique characteristics of a particular disaster within a robust decision making framework is of profound significance. One of the steps taken by the Federal government in this regard was the formation of the Strategic National Stockpile (SNS) (CDPH, 2013; NACCHO, 2013). As described by the CDC, the "SNS has large quantities of medicine and medical supplies to protect the American public if there is a public health emergency (terrorist attack, flu outbreak, earthquake) severe enough to cause local supplies to run out". Specifically, once federal and state authorities come to a consensus that these supplies are needed, an immediate request is made to ensure they are deployed in a timely manner.

While the current SNS configuration can significantly improve response efforts via prepositioning of supplies for disasters such as hurricanes for which there is forewarning, such a privilege does not exist for unanticipated disasters. Hence the delivery of supplies under the current framework may turn out to be too little too late for these types of events. This issue can in part be attributed to the gaps that exist within the current research in developing strategic plans based upon a risk assessment for a given region. For example, existing models pertaining to the planning of the locations and capacities of emergency supplies in the event of an earthquake, which we devote specific attention to, do not account for the uncertainty due to topographic and geological characteristics of the region, uncertainty related to facility damage, nor the number, severity and medical condition of the resulting casualties. Other factors that could impact the location-allocation decisions include budgetary constraints, uncertainty in transport times, as well as facility costs as a function of capacity and building structure. Such investigations in the extant literature have been notably lacking. These questions form the motivation for this research endeavor.

* Corresponding author. Tel.: +1 470 578 6579; fax: +1 470 578 9022.
E-mail address: lmacdon4@kennesaw.edu (L. MacDonald).

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To address this gap in the literature, we first propose a generic framework applicable to planning in the event of an unexpected disaster, particularly when the primary goal is to establish stockpiles of necessary medical supplies to minimize fatalities. We then demonstrate the proposed approach, developing a stochastic optimization model to determine the location and capacities of regional distribution centers (DC) for improved preparedness in the event of an earthquake. Our models incorporate facility and casualty losses as a function of the earthquake magnitude and its interaction with factors such as the population at demand nodes, building code (i.e. resistance to damage), transport time to a demand center, etc. We model the casualty numbers at the demand nodes as well as their mix in terms of severity and associated survivability time following Paul and Hariharan (2012). In addition, to address the issue of computational complexity associated with problems of realistic size, we develop a heuristic solution that builds on the principles of the Evolutionary Optimization (EV) algorithm. This is further aided by an innovative mixed integer programming (MIP) model that provides a high quality initial solution to the EV. Finally, we use a decision analysis model to generate solutions that are robust to the specific characteristics of the region. We then demonstrate the effectiveness of our modeling approach via a case study featuring the Northridge region in California.

The remainder of the article is organized as follows. In Section 2 we present a review of the current literature. Section 3 presents a description of our generic framework, followed by a statement of the problem of interest as well as the model notations and the mathematical formulation. In Section 4 we develop the evolutionary optimization based heuristic, including an innovative MIP model that generates a high quality starting solution for the heuristic when solving large-scale problems. Section 5 demonstrates the effectiveness of the heuristic in generating high quality time efficient solutions via a case study, in addition to discussing various key data considerations and the methodologies employed to derive them. We then employ decision analysis models to develop a solution that is robust to earthquake magnitude, taking into account the geological characteristics of the region. Finally, Section 6 presents our conclusions and provides directions for future research.

2. Literature review

Determining the location and capacities of DCs for the prepositioning of supplies to support treatment centers in the delivery of care to those affected by a disaster is a multifaceted problem. This has resulted in a large body of literature that evaluates the various aspects and factors that impact the location-allocation problem. Within this review of the extant literature, we primarily focus on facility location, with a special emphasis on the prepositioning of supplies for humanitarian relief and decision making under uncertainty. Those interested in a broad overview of the recent advances in disaster operations management should refer to the article by Galindo and Batta (2013a). A summary of earlier work may also be found in Akkihal (2006). Altay and Green (2006) develop a mixed integer programming model for determination of the optimal locations of facilities to be used to preposition inventory for improved relief efforts. Jia, Ordonez, and Dessouky (2007) develop models to determine the optimal positioning of emergency medical service (EMS) facilities during large scale emergencies such as bioterrorist attacks. Balcik and Beamon (2008) find optimal locations and capacities of warehouses designed to store prepositioned relief supplies. An underlying assumption in their analysis is that demand for relief supplies can be met by the suppliers. Huang, Kim, and Menezes (2010) consider disruptions and access issues related to service facilities within a given demand center when determining the optimal facility locations in their study featuring large scale emergencies. Duran, Guitierrez, and Keskinocak (2011) develop an MIP model to determine the number and location of prepositioned warehouses that would enable a humanitarian organization (CARE International) to deliver necessary relief supplies in an optimal and timely manner to those impacted by a disaster. In contrast to the prior work by Balcik and Beamon (2008), they allow for multiple events to occur within a replenishment period, as well as for the probability of demand to depend on both local conditions and the type of natural disaster.

Determining the strategic location and capacities of DCs for the prepositioning of supplies within a region prone to a natural disaster is well suited to decision making under uncertainty. Lee et al. (2006) develop robust decision support tools for planning emergency dispensing clinics in their study featuring biological threats such as Anthrax and Smallpox. Determination of the required staffing levels to dispense the necessary supplies while considering the disaster uncertainty forms the primary focus of their models. Lodree and Taskin (2011) use a stochastic inventory control modeling approach to determine the locations and capacities of emergency shelters. The final location-allocation decision is based on the tradeoff between logistical cost efficiency and forecast accuracy. Li, Jin, and Zhang (2011) develop a two-stage stochastic programming model to handle both the evacuee flows and the distribution of resources that are required to support shelter operations. Specifically, the first stage determines the locations, capacities, and held resources for the new permanent shelters, while the second stage allocates evacuees as well as transports resources to individual shelters. Rawls and Turnquist (2010) develop models that determine the supply locations from a set of potential sites. Based upon a probabilistic scenario approach, they then develop a distribution plan that considers the possible loss of prepositioned supplies. In an extension of this work, Noyan (2012) introduces risk aversion measures in addition to the expectation criterion employed by Rawls and Turnquist (2010). In a follow-up to their previous study, Rawls and Turnquist (2012) develop a dynamic allocation model for prepositioning supplies at storage locations for meeting demands resulting from a disaster. Additionally, their models develop a distribution plan based upon a probabilistic scenario-based approach, wherein the loss of prepositioned supplies is considered as a possibility. In the context of a bio-terror attack, Murali, Ordonez, and Dessouky (2012) determine dispensing locations via a special case of a maximal covering location problem. Demand uncertainty is incorporated via chance constraints, with a loss function to address distance dependent demand.

In Salmeron and Apte (2010), the authors present a scenario analysis involving a two-stage stochastic optimization approach for the location, allocation and distribution decisions for the prepositioning of supplies. The first stage deals with establishing facilities with the goal of minimizing casualties. In the second stage, the model focuses on determination of both the distribution of supplies as well as the associated casualties, including possible evacuation, with the goal of minimizing the number of casualties that go without service. Paul and Hariharan (2012) develop models that incorporate both scenario planning and robust optimization for stockpile location and capacity allocation for regions prone to earthquake and hurricane disasters. In Davis, Samanlioglu, Qu, and Root (2013), the authors propose a stochastic programming model for the location and allocation of supplies for disaster relief involving a pending disaster. The model incorporates up to date forecasts as well as post event distribution.

Galindo and Batta (2013b) develop a model for prepositioning of supplies in preparation for hurricane disasters that have some forewarning, and allow for the possible damage or destruction of prepositioned supplies. The stochasticity of demand is taken into account through the use of amplifying factors. Kelle, Schneider, and Yi (2014) extend this by integrating the evacuation and sheltering phase into the supply problem. Their work builds on contributions by Li et al. (2011), by extending the expected value criterion to regret consideration, and the supply chain to a hierarchical network of sup-