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A stochastic programming approach for floods emergency logistics

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ABSTRACT

This article presents a model to assist decision makers in the logistics of a flood emergency. The model attempts to optimize inventory levels for emergency supplies as well as vehicles' availability, in order to deliver enough supplies to satisfy demands with a given probability. A spatio-temporal stochastic process represents the flood occurrence. The model is approximately solved with sample average approximation. The article presents a method to quantify the impact of the various intervening logistics parameters. An example is provided and a sensitivity analysis is performed. The studied example shows large differences between the impacts of logistics parameters such as number of products, number of periods, inventory capacity and degree of demand fulfillment on the logistics cost and time. This methodology emerges as a valuable tool to help decision makers to allocate resources both before and after a flood occurs, with the aim of minimizing the undesirable effects of such events.

1. Introduction

Most of the logistics systems are designed to operate under regular conditions. Even under these conditions the logistics strategy and operation encompass rather difficult tasks to accomplish. This already difficult situation becomes even more cumbersome when the system's components exhibit uncertainty. That is the case when a flood takes place. The United States Geological Service defines a flood as a relatively high streamflow overtopping natural or artificial banks in any reach of a stream (Holmes and Dinicola, 2010). Floods are most likely to take place when water from heavy rainfall, melting ice or snow exceeds the flow capacity of a river system, lake, etc. Usually floods are the result of a compounded flow of various tributaries with excess flow taking land on riverbanks or a shoreline. According to Pelling et al. (2004), an average of more than 196 million people are affected by a disastrous flood each year around the globe. The human and wildlife losses can be enormous and economic loss from flooding of residential and non-residential properties can reach significantly high levels. For example, the UK Environment Agency estimated that during the 2012–2013 season (excluding fatalities), about £200 and £277 million worth of damage was attributable to floods in the United Kingdom (UK-Environment-Agency, 2013); those figures exclude other major impacts, such as disruption to transportation networks and indirect impacts on communities and local businesses. They also point out that the total damage could have reached up to £7.5 billion, in the absence of flood preparedness. Decision makers (DM) need tools to mitigate the effects of floods because the number of actions that can be taken under a disaster of this kind is enormous (e.g., where to stock supplies, how much inventory to hold, fleet size, etc.) and

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the impacts of those actions are hard to estimate beforehand. Unfortunately, comprehensive planning tools for floods currently do not exist (Chang et al., 2007).

People affected by a flood need prompt attention in several dimensions: health care, food, water, safety, and childcare among others. The means to deliver the assistance is usually damaged and hence the standard supply plans do not hold in the disastrous scenario. Additionally, improvised logistics plans to reach the affected area with all the urgent needs have proven to fail due to the lack of information and preparedness (see for example Holguin-Veras et al., 2007). The mitigation of effects on the population is highly dependent on the time to reach and assist the victims. In fact, Hu and Sheu (2013) present a methodology to minimize not only the standard costs of a disaster but also the psychological trauma experienced by people affected by an earthquake while they waited for assistance. The psychological trauma was established as an increasing marginal function of the waiting time for assistance. The latter suggests that the time dimension is as important as the cost dimension to be minimized.

The design of a flood disaster response plan includes maintaining and locating/allocating rescue equipment, budget, and human resources at specific places in advance, i.e., there are actions to perform both before and after the disaster occurs. Once the flood has occurred, the victim's assistance can be launched in an orderly manner. Following Chang et al. (2007) logic, basic flood emergency operations should consider the division of the affected area into several zones and emphasize intra-zonal distribution and inter-zonal backup. Under such a system, the flood emergency logistics network emerges as a multi-zone, multi-echelon, and multi-level graph. Consequently, this article deals with a network optimization model to assist DM in the pre-disaster stages and the aftermath of a flood. The relevance and merit of the methodology developed in this research is to have found a way to solve a difficult network optimization model which can be properly interpreted to offer recommendations to the DM before and after a flood occurs. The model's solution will provide guidance about pre-positioning emergency supplies and vehicles, as well as the flows of materiel over a transportation network to reach the affected areas at minimum time and cost. The outcome of the modeling framework can be translated into a set of recommendations to the DM, from which certain inputs are needed, such as the demand satisfaction level (i.e., the minimum acceptable percentage of successful delivery of emergency supplies), the characteristics of flood scenarios (i.e., the expected correlations between flood occurrences in different locations and periods), as well as the available resources.

In this article we take advantage of the fact that floods exhibit a seasonal and/or spatial recognizable pattern that can be adequately represented by a stochastic process. This approach has been widely studied in the technical literature as well as in practice by public agencies around the world (see for example Cunnane, 1987). Consequently, both the occurrence of floods and their severity are treated as random variables in this study. Though the loss of transportation capacity is a relevant point when dealing with floods, its consideration as a probabilistic-combinatorial event in an approach that explicitly incorporates network damages is still intractable when combined with the uncertainties studied in this article, and hence the network status after a flood is considered to be a parameter of the problem under analysis.

The proposed methodology is unique with the following five distinctive features:

- The demand for emergency supplies associated with a flood is explicitly incorporated as a stochastic variable with a magnitude proportional to the intensity of the flood.
- Flood occurrences are simulated through a stochastic process that incorporates the most prominent features of a flood: simultaneous spatial and temporal correlations, as well as a flood intensity, following the concept of Exceedance Probability (EP).
- The objective to be optimized is expressed in terms of a generalized cost function, which in this case is a linear combination of two logistics parameters: distribution time and distribution cost. This function also allows considering the inclusion of other parameters into the same function; this linear combination forms a single score to be minimized.
- The demand for emergency supplies must be satisfied to a certain level of service (usually $\leqslant 100\%$). DM want to maximize the number of beneficiaries they can assist with the available budget. However, it would be beneficial for them to know what proportion of the total affected population their budget can actually serve. This modeling framework allows the DM to simulate both the cost of serving a given population and/or the percentage of covered population that a given budget can achieve.
- Due to the distinctive characteristics of floods occurrences and level of service for demand satisfaction, a stochastic optimization model is formulated to integrate not only cost but also time and availability of supplies and vehicles simultaneously.

Thus, the gap that this paper aims to fill is the simultaneous consideration of these features within a modeling framework that in spite of being highly complex it can be solved, at least to a feasible solution. The solution provides DM with a strategic plan to implement before a flood occurs as well as a tactical plan to deliver emergency supplies after the flood has occurred.

2. Literature review

Given the relevance of emergency logistics, a number of specialized articles on this subject are gradually appearing in the technical literature. In fact, a recent study on humanitarian logistics (Leiras et al., 2014) finds about 200 articles in this general topic (both methodological and descriptive). This section attempts to give a general perspective of the methodological