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A three-stage stochastic facility routing model for disaster response planning

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ABSTRACT

This paper presents a three-stage mixed-integer stochastic programming model for disaster response planning, considering the opening of local distribution facilities, initial allocation of supplies, and last mile distribution of aid. The vehicles available for transportation, the state of the infrastructure and the demand of the potential beneficiaries are considered as stochastic elements. Extensive computational testing performed on realistic instances shows that the solutions produced by the stochastic programming model are significantly better than those produced by a deterministic expected value approach.

1. Introduction

Natural disasters such as droughts, earthquakes, hurricanes and floods have proven a global challenge in their unpredictable nature and potential scale of impact represented by fatalities and social, environmental and economic costs. The Haiti earthquake of 2010 demonstrated the potential severity of events following a natural disaster. It killed 222 570 people and affected a total of 3.9 million others. The disaster caused an estimated US$ 8.0 billion worth of damages, and led to the collapse of around 70% of buildings and homes (Guha-Sapir et al., 2011).

In 2011, 302 natural disasters claimed over 29,780 lives worldwide, affected nearly 206 million others and caused record economic damages of US$ 366 billion (Guha-Sapir, 2012). In 2012, over 11 000 lives lost and US$ 140 billion damages have been estimated (Swiss Re, 2012). These figures substantiate the importance of providing aid of the appropriate kind and amount to those affected in the most efficient and effective way possible, to prevent loss and suffering (Christopher and Tatham, 2011). Due to the high magnitude and economical impact of disasters, advances in the management of disaster operations are imperative, and will contribute to an improvement in readiness, increase response speed, ease recovery and provide institutional learning over time (Altay and Green, 2006; Christopher and Tatham, 2011; de la Torre et al., 2012; Thomas and Kopczak, 15(16th).

The function concerning the process of distributing required aid and supplies in disaster relief situations is often referred to as humanitarian logistics. This term is widely used, and covers operations ranging from supply chain strategies and processes to technologies which will maintain the flow of goods and materials required by the humanitarian agencies (Baldini et al., 2011). At its simplest, the operations involve procurement, dispatch of aid for shipment to the beneficiary region, storage in either national or regional warehouses, and eventually transport to the extended and final distribution points where the aid is handed to the beneficiaries (Maspero and Ittmann, 2008). Movement of goods and people accounts for up to 80% of

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the costs in any disaster relief operation, making it the most expensive part of the operation (Clark and Culkin, 2013; Sangiamkul and Hillegersberg, 2011).

Uncertainty and unpredictability characterizes the surroundings of disasters, and the logistical activities are to be performed in rapidly changing environments. Knowledge of timing and location of events is substantially difficult, if not impossible, to predict with any significant degree of certainty (Christopher and Tatham, 2011). The same applies to the total magnitude of events immediately following a disaster. This translates into a number of different aspects: uncertainty regarding the nature of demand, capacity of facilities to be used in the distribution process, the transportation capacity, and amount of supply available for the decision maker, along with several other factors. Adding to this is the implicit urgency of need. Not only is the decision maker in charge of the distribution process required to make decisions based on limited and unreliable information, he must also make these at the earliest possible point in time following a disaster in order to prevent lives from being lost (Altay and Green, 2006; de la Torre et al., 2012).

Against a backdrop of uncertainty, the aim of this paper is to present an optimization model for a location and routing problem with stochastic elements that can be used for planning the distribution of aid following a catastrophic event. A three-stage stochastic model is proposed, capturing uncertainty in demand, capacity of the vehicle fleet and the state of the infrastructure. The initial stage concerns facility location decisions, regarding the opening of distribution centers, whereas the last two stages involve last mile distribution decisions: amount of aid to be delivered to each recipient, types of vehicles to be used for transportation and itineraries to be followed. The model captures the flow of multiple commodities using multiple modes of transportation, considering explicitly several vehicle types with different characteristics, and the goal is to maximize the utility provided by covering the demand for different commodities.

Clark and Culkin (2013) propose three principles said to define humanitarianism: humanity, impartiality and neutrality. In short, these state that suffering should be alleviated wherever it is found, giving priority to the most urgent needs without discrimination. The concept of fairness is vital to consider when distributing emergency supplies. The Sphere Handbook (The Sphere Project, 2011) argues that agencies should provide aid impartially and in accordance with need. Generally, the needs of the most vulnerable sub-groups of the population, such as wounded, children and pregnant women, are prioritized. Consequently, the marginal utility of the delivered items diminishes in line with reception of aid by the most indigent. Even though need for relief may still exist in an area, helping people of higher levels of distress in other regions before continuing to deliver to the initial region might be of greater utility. Fairness in the distribution of aid will be taken into account by the model.

The remainder of the paper is organized as follows. Section 2 reviews the main papers available in the literature related to the topic considered, highlighting the main differences with the approach proposed in this paper. Section 3 gives a detailed description of the disaster response problem approached, whereas a three-stage stochastic programming model for this problem is presented in Section 4. An extensive computational study and an application of the model to instances based on the Haiti earthquake of 2010 are presented in Section 5, while concluding remarks are given in Section 6.

2. Literature review

The main differences between business logistics and humanitarian logistics include the objectives to be optimized (maximizing profit or minimizing costs in contrast to minimizing time of response or maximizing fairness of distribution) and the circumstances in which operations are to be performed (known resources and infrastructure in contrast to uncertainty regarding supplies, available vehicles and the condition of the road network). However, there are also similarities, including the combination of routing decisions and location decisions, as found in this paper in the context of humanitarian logistics. A survey on models for combined location-routing problems in business logistics is available in Min et al. (1998), and a more recent survey can be found in Nagy and Salhi (2007). Due to the important differences between business logistics and humanitarian logistics stated before the remaining of this section is restricted to the literature in humanitarian logistics.

The number of studies conducted in this area since its onset in the 1990s, has seen an increase in line with the impact of disasters (Van Hentenryck et al., 2010). Different scholars have covered a variety of different classic models such as vehicle routing, network flow, facility location, location routing and supply chain management, in order to best describe the mechanisms of the humanitarian supply chain. The different aspects related to the humanitarian supply chain are reflected in the level of complexity of the models.

Various approaches are taken by different scholars in terms of their choice of focal point within the humanitarian supply chain. The relationship between central depots providing initial supplies to local distribution centers is among the most common choices of tier (Balcik and Beamon, 2008; Campbell and Jones, 2011; Yi and Özdamar, 2007). These models are mainly restricted to determining the number and location of local distribution centers to initialize, in addition to the amount of supply to be stocked at the distribution centers chosen. Last mile distribution considering the final stage of humanitarian logistics is another widely applied practice (Balcik et al., 2008; Barbarosoğlu and Arda, 2004; Hsueh et al., 2008; Nolz et al., 2010; Özdamar et al., 2004; Shen et al., 2009b,a; Vitoriano et al., 2009, 2010). These models aim to develop vehicle schedules in order to allocate supplies between the affected population from the available pre-established distribution centers. Several scholars have also chosen to consider a wider part of the supply chain, integrating decisions concerning both pre-positioning of emergency supplies and last mile distribution of these supplies (Günneç and Salman, 2007; Van Hentenryck et al., 2010;