European Journal of Operational Research 255 (2016) 187–206

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Innovative Applications of O.R.

Stochastic network models for logistics planning in disaster relief

Douglas Alem[a,*], Alistair Clark[b], Alfredo Moreno[a]

[a] Production Engineering Department, Federal University of São Carlos, Sorocaba, Brazil
[b] Department of Engineering Design and Mathematics, University of the West of England, Bristol BS16 1QY, United Kingdom

ARTICLE INFO

Article history:
Received 19 November 2015
Accepted 21 April 2016
Available online 4 May 2016

Keywords:
OR in disaster relief
Humanitarian logistics
Emergency logistics planning
Two-stage stochastic programming
Risk-aversion

ABSTRACT

Emergency logistics in disasters is fraught with planning and operational challenges, such as uncertainty about the exact nature and magnitude of the disaster, a lack of reliable information about the location and needs of victims, possible random supplies and donations, precarious transport links, scarcity of resources, and so on. This paper develops a new two-stage stochastic network flow model to help decide how to rapidly supply humanitarian aid to victims of a disaster within this context. The model takes into account practical characteristics that have been neglected by the literature so far, such as budget allocation, fleet sizing of multiple types of vehicles, procurement, and varying lead times over a dynamic multiperiod horizon. Attempting to improve demand fulfillment policy, we present some extensions of the model via state-of-art risk measures, such as semideviation and conditional value-at-risk. A simple two-phase heuristic to solve the problem within a reasonable amount of computing time is also suggested. Numerical tests based on the floods and landslides in Rio de Janeiro state, Brazil, show that the model can help plan and organise relief to provide good service levels in most scenarios, and how this depends on the type of disaster and resources. Moreover, we demonstrate that our heuristic performs well for real and random instances.

1. Introduction

Floods and landslides are just two of the various types of disaster that plague Brazil year after year, leaving a trail of huge destruction. According to Valencio (2014), the problem of disasters in Brazil should not be considered *residual*; it suffices to analyse the number of municipalities which declared an *emergency situation* or *state of public calamity* between the years 2003 and 2013 to confirm that disasters are, in fact, recurrent events. During this period, an average of 1368 municipalities, about 24 percent of Brazilian municipalities, had some sort of socioeconomic problem as a result of environmental disasters – from droughts in the northeast to flooding in the south region. In the same line, Yodmani (2001) argues that disasters should not be seen as simply extreme events caused only by natural forces, but also as symptoms of underdevelopment in countries.

In July 2013, the Civil Defense of Brazil and its Postal Service signed a contract for the prepositioning of strategic stocks for humanitarian assistance in certain regions of the country in an attempt to mitigate disaster impacts (Presidency of the Republic, Brazilian Government, 2013). The main idea behind such a policy is to provide a faster response, possibly by decreasing lead times between the request and arrival of supplies. For this purpose, though, an optimized system is needed to cross-check information about safety stocks (location, availability, etc.) with updated information about the disaster (e.g., affected areas, number and need of the victims, road damage) and to determine the quantity and sizes of existing vehicles required to deliver supplies. Such prepositioning, without mentioning the provision of emergency relief and supplies to disaster victims, is fraught with planning and operational challenges (Balcik, Beamon, Krejci, Muramatsu, & Ramirez, 2010) mostly due to the scarcity of overall resources and the inherent uncertainties of disasters.

Thus, in order to respond to disasters effectively, governments and humanitarian organisations need to consider these issues when designing effective relief supply chains. However, Gonçalves (2011) showed that humanitarian decision makers often make non-optimal decisions in the field by over-reliance on past experience, over-confidence in their own unaided decision-making abilities, and the use of simple decision heuristics. The resulting poor decisions motivate this paper to explore stochastic and dynamic models that can handle the urgent complexity and uncertainty faced by decisions makers. In particular, we propose an optimization model that could be used within a decision-aid tool by the Brazilian agencies that are currently responsible for providing rapid responses in disaster relief. Our model encompasses common decisions

* Corresponding author. Tel.: +55 1532297425.
E-mail address: douglas@ufscar.br (D. Alem).

http://dx.doi.org/10.1016/j.ejor.2016.04.041

regarding logistics planning, such as how to dispatch emergency aid from warehouses to affected areas over a number of time periods in order to alleviate suffering during relief operations, that is, to decide the most suitable routes, which vehicles should be used, in which periods and in which quantity, and so on.

The model also balances the immediate lack of external supplies by allowing (i) the procurement of emergency aid during a response; and (ii) the prepositioning of emergency aid before a disaster strikes. The first option is based on Brazilian humanitarian practices where procurement usually occurs some days or more after the start of the humanitarian operations in the same area where the disaster struck. However, only a few emergency aid items are likely to be available, in very limited amounts and at a very high cost, since local vendors often take advantage of the vulnerable situation. The second option may be seen as a global trend to overcome the suddenness of disasters (Davis, Samanlioglu, Qu, & Root, 2013; Duran, Gutierrez, & Keskinocak, 2011; Lodree, Ballard, & Song, 2012; Salmerón & Apte, 2010). Additional decisions supported by the proposed model concern defining appropriate inventory levels and budget allocation among the various operations. Backlogging is permitted at a very high cost, as we know that in practical problems there are not enough resources to meet the demand from all victims.

For Oztaysi, Behret, Kabak, Sari, and Kahraman (2013), uncertainty is a crucial challenge that must be overcome in disaster management. In fact, immediately after or during a natural disaster, the number of affected people (homeless, displaced, injured, deaths) may be only vaguely known and recipient demand will be difficult to predict in terms of timing, location, type, and size. Suddenly-occurring large demand and short lead times for a wide variety of supplies will contrast with periods of low demand (Kovács & Spens, 2009; Sarkis, Spens, & Kovács, 2010). In addition, since the situation is often unclear in the immediate aftermath of the disaster, some routes might be total or partially blocked, with uncertain information about any damage. In the megadisaster of the *Serrana* region of Rio de Janeiro (Brazil) in 2011, 14 state highways from 7 different cities suffered traffic blockages due to landslides and flooding, besides the countless number of urban and rural access roads that were also damaged. Although many emergency aid supplies can be strategically prepositioned, only some of them will remain usable, depending on the impact and location of the disaster.

Supplies and monetary funds may also be affected by the degree of the disaster. Recent studies suggest that donor behaviour may depend not only on measurable parameters – such as an aid agency's use of donated funds, fund-raising cost factors, and donors' unit utility of donations Toyasaki and Wakolbinger (2014) – but also on subjective factors that influence the decision to donate, such as how people perceive a certain disaster (Zagefka, Noor, Brown, de Moura, & Hopthrow, 2011), and the role of the media, social networks, etc. (Brito Junior, Leiras, & Yoshizaki, 2013). As supplies and monetary budgets usually come from a variety of organisations, they are considered to have uncertain values as well. This uncertainty is further complicated by the phenomenon of material convergence (Fritz & Mathewson, 1957; Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012) whereby well-meaning non-professional donors supply huge quantities of unsolicited goods of doubtful usefulness that can (and often do) clog the supply chain, disrupting the flow of urgent aid to recipients in need.

In this paper, uncertainties are modelled via scenario-based two-stage stochastic programming. The first-stage plans the prepositioning of emergency aid and the overall capacity of each type of vehicle (fleet-sizing). The second-stage response makes operational decisions for transportation – including the detailed decision regarding the assignment of vehicles to routes – as well as inventory, shortages, and procurement. The objective function is flexible, being able to minimise total expected costs or prioritize the meeting of recipient demand while avoiding excessive inventory. We also show how that the stochastic programming model can be straightforward extended to consider different risk-averse preferences to produce less risky or reliable solutions and/or to improve fairness.

As the mixed-integer stochastic programming models are huge and computationally challenging even for small-sized instances, we develop a two-phase heuristic that performs very well for real and random instances. The first phase solves a (smaller) simplified version of the model that overestimates the overall number of vehicles in the first-stage. The second phase then fixes the first-phase decisions regarding the operational distribution flow and re-solves the original model to determine the remaining decision variables.

Our overall numerical results have important implications in terms of roles within the humanitarian supply chain in efficiently managing both the preparedness and response phases of most sudden-onset disasters.

This paper is organised as follows. Section 2 reviews the most relevant literature. Section 3 develops the proposed stochastic optimization model. Section 4 shows how to extend the risk-neutral stochastic model to incorporate risk preferences. Section 5 presents a two-phase procedure to determine good-quality solutions within a reasonable amount of time. Section 6 implements the model on real data from the 2011 floods and landslides in Rio de Janeiro state, Brazil, and analyses the computational results. The paper concludes in Section 7 with a discussion of the model's value and flags remaining challenges and opportunities for future research.

2. Related literature

Possibly due to the increased frequency and severity of disasters around the world and to their greater visibility on television and social media in recent decades (Franks, 2014; Seib, 2014), these wrenching events have been the subject of growing public concern and research interest (Smith, Wasiak, Sen, Archer, & Burkle, 2009). This paper will not review all decision models for disaster management and emergencies, but rather will focus on the quantitative management of uncertainty in emergency logistics planning in disaster relief, considering only recent research on scenario-based stochastic programming approaches in transportation and distribution relief within network flows. The reader who is interested in wider surveys of the application of quantitative models and operational research to humanitarian logistics can consult Altay and Green (2006), Van Wassenhove (2006), Caunhye, Nie, and Pokharel (2012), De la Torre, Dolinskaya, and Smilowitz (2012), Holguín-Veras et al. (2012), Ortuño et al. (2013), Galindo and Batta (2013), Leiras, de Brito Jr, Queiroz Peres, Rejane Bertazzo, and Tsugunobu Yoshida Yoshizaki (2014) and Özdamar and Ertem (2015) amongst others.

Two-stage stochastic programming with recourse models have been successfully used in humanitarian logistics and disaster management as they allow the modeller to represent pre- and post-event phases together via first- and second-stage decision variables. Barbarosoğlu and Arda (2004) appears to be the pioneer paper that developed a two-stage stochastic model for both pre-event and post-event stages in disaster response, considering supply capacity and demand as random variables approximated by multiple scenarios. In addition, following a two-stage paradigm, but with different first- and second-stage decisions, Chang, Tseng, and Chen (2007) presented a scenario-based model adapted to represent a multi-echelon network in a flood disaster rescue system.

Relief resource allocation problems have also been researched in the following papers. Mete and Zabinsky (2010) designed a two-stage stochastic model to first locate possible medical storage centres and their stock levels before the disaster, then to deliver