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An effective two-stage stochastic multi-trip location-transportation model with social concerns in relief supply chains

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ABSTRACT

The distribution of emergency aid from warehouses to relief centers to satisfy the needs of the victims in the aftermath of a disaster is a complex problem because it requires a rapid response to human suffering when resources are scarce amidst great uncertainty. In order to provide an effective response and use resources efficiently, this paper presents a novel model to optimize location, transportation, and fleet sizing decisions. In contrast with existing models, vehicles can be reused for multiple trips within micro-periods (blocks of hours) and/or over periods (days). Uncertainty regarding demand, incoming supply, and availability of routes is modeled via a finite set of scenarios, using two-stage stochastic programs. 'Deprivation costs' are used to represent social concerns and minimized via two objective functions. Mathematical programming based heuristics are devised to enable good-quality solutions within reasonable computing time. Experimental results based on data from the disastrous 2011 floods and landslides in the Serrana Region of Rio de Janeiro, Brazil, show that the model's novel characteristics help get aid faster to victims and naturally enforce fairness in its distribution to disaster areas in a humanitarian spirit.

1. Introduction

Brazil's *National System for Protection and Civil Defense* (SINPDEC) manages the country's emergency preparedness and response to severe disasters. Its main role is to reduce the impact of disasters in vulnerable communities, and so mitigate human suffering and preserve the population's well-being (Valencio, 2010). The increasing number of affected people and the economic damage caused by disasters in recent years have highlighted the difficulty that organizations such as SINPDEC face in responding effectively to the various types of disasters that plague Brazil. For example, in one of the country's worst socio-environmental disasters, the so-called Megadisaster of the Serrana region of Rio de Janeiro state in 2011, floods and landslides claimed more than 1,000 lives and left around 30,000 people displaced and homeless. Experts assess that this scale of impact was due to the lack of well-structured contingency plans and coordination problems between the different bodies involved in the initial response phase.

Clearly, part of the problem is due to the unpredictability and complexity of such disaster events. The needs of victims are difficult to forecast and can arise with little or no warning. There is a mismatch between supply and demand, as the latter may depend on the uncertain behavior of in-kind donations (Barber, 2012). Transport links may be poorly mapped, only partially functional, or destroyed. Transport to distribute relief supplies may not be readily available. Moreno, Alem, and Ferreira (2016) also points out that "... multiple agencies may be trying to satisfy the same perceived need in an uncoordinated manner, just as commercial competitors do, but with little prior information about needs, resulting in over and under supply with consequent human suffering and avoidable deaths". These problems can be even more challenging in developing economies where relief resources are usually scarce and thus not sufficient to fulfill people's needs in the aftermath of a disaster.

This paper handles this complexity by proposing a novel integrated approach to improve distribution logistics in disaster situations under uncertainty. Our optimization model integrates key preparedness and response activities for an effective disaster management, such as location of relief centers and transportation of emergency aid, which includes fleet-sizing decisions in both pre- and post-disaster phases. Each single vehicle is allowed to make several journeys within the period and over the time horizon without restricting the period's length, economizing overall resources. Typical uncertainty data such as victims' needs,

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incoming supplies, and route availability is modeled via a set of discrete scenarios and incorporated in the optimization model following the two-stage stochastic programming paradigm.

Furthermore, we propose two approaches to take into account social concerns during relief operations, both based on the concept of deprivation costs that victims incur due to the lack of emergency aid. One approach prioritizes the minimization of deprivation costs over logistics costs, while the other, minimizes logistics and deprivation costs jointly in a single objective function as Holguín-Veras, Pérez, Jaller, Van Wassenhove, and Aros-Vera (2013). Overall results in this paper show that it is possible to mitigate human suffering via a more effective demand fulfillment policy based on deprivation costs in either mono- or bi-objective fashion. In fact, the main findings clearly show that deprivation costs help to provide a more equitable solution amongst the different affected areas and, simultaneously, providing good service levels as much as possible given the scarcity of resources.

The computational results are analyzed with data instances based on the disastrous 2011 floods and landslides in the Serrana Region of Rio de Janeiro, Brazil. We also devised three heuristic strategies to provide good-quality solutions within reasonable elapsed times for our practical instances: a fix-and-optimize heuristic; a two-step heuristic based on an approximate linear programming model; and a hybrid heuristic that combines the fix-and-optimize and the two-step heuristics. Even though developed with reference to a particular Brazilian case, the numerical results have general relevance for the efficient management of such humanitarian supply chains over a myriad of sudden-onset disasters.

The rest of the paper is organized as follows. Section 2 presents the literature review. Section 3 describes the problem and presents the mathematical model. Section 3.1 develops the solution methods. Section 3.2 discusses the computational results. Finally, Section 3.3 presents the final remarks and future research.

2. Literature review

This paper's literature review focuses on integrated disaster logistics models with multiple trips and deprivation costs, looking at three streams. The first stream (i) concerns recent modeling approaches for integrating distribution, fleet sizing and/or location decisions. The second stream (ii) focuses on how existing approaches have incorporated partial multiple trips. Finally, the third stream (iii) reviews the few models with deprivation costs. The key papers in each category are exhibited in Table 1, which summarizes the main characteristics, decisions, and objective functions of their corresponding optimization approaches, showing their main differences with this paper.

Most studies that developed integrated models for coordinating preparedness and response activities in humanitarian logistics focused on multi-period settings. However, most multi-period models overlooked the uncertainty about the number of affected people and their needs (Afshar & Haghani, 2012; Lin, Batta, Rogerson, Blatt, & Flanigan, 2012; Vanajakumari, Kumar, & Gupta, 2016; Yi & Ozdamar, 2007). Recognizing the inherent uncertainty in disaster operations, such as the needs of victims, route availability, supplies, and shipping time, various authors have proposed two-stage stochastic programming models, often representing pre-disaster preparedness as first-stage decisions and post-disaster response as second-stage decisions (Ahmadi, Seifi, & Tootooni, 2015; Mete & Zabinsky, 2010; Rath, Gendreau, & G utjahr, 2016; Salmerón & Apte, 2010).

A few papers have attempted to handle multiperiod and stochastic issues in a scenario-based, two-stage paradigm (Bozorgi-Amiri & Khorsi, 2016; Moreno et al., 2016). Fleet (re)sizing is an important recourse decision to hedge against severe uncertainty in post-disaster situations, but this option was adopted only in Moreno et al. (2016). However, in these studies there is still potential to save overall resources by considering the option of reusing the vehicle fleet over the time horizon and within each period, respectively. Note that, although many papers have considered reusing vehicles, with exception of Moreno et al. (2016), none have explicitly discussed this issue nor its benefits in relief distribution.

In this paper, we propose to define the concept of the "partial multi-trip" when vehicles are assumed to be used only once by each period over the time horizon or several times within a period, but without exceeding the period's length. Perhaps surprisingly, only a few papers permit the (re)utilization of vehicles for partial multiple trips within fleet sizing decisions. Two cases are considered: (i) partial multiple trips over the time horizon; or (ii) partial multiple trips within each time period.

In case (i), travel times are assumed to be multiples of the period length. For example, day-long periods lead to travel times of 1 day, 2 days, etc. This approach is not accurate when travel times are much shorter than a period. If, for example, a travel time last 2 hours and the period length is a day, then during the 22 subsequent hours the vehicle is considered "not available" and cannot be used again until the next day. This limited option of reusing vehicles featured in Afshar and Haghani (2012); Ozdamar, Ekinci, and Kucukyazici (2004); Yi and Kumar (2007); Yi and Ozdamar (2007) and Pérez-Rodríguez and Holguín-Veras (2015). While Ozdamar et al. (2004) minimized only the unsatisfied demand, Yi and Kumar (2007) used a weighted-sum function of unmet demand and untreated wounded victims and Pérez-Rodríguez and Holguín-Veras (2015) considered "social costs" via a single objective function composed of logistics and deprivation costs.

In case (ii), vehicles can be reused within the same time period to perform more than one trip. This approach is recent and seems to be more efficient than case (i), but travel times are assumed to be shorter than a period's length and departures in one period cannot arrive in subsequent periods. This case includes integrated models with facility location (Bastian, Griffin, Spero, & Fulton, 2016; Bozorgi-Amiri & Khorsi, 2016; Moreno et al., 2016) and without (Ferrer, Ortuño, & Tirado, 2016; Lin, Batta, Rogerson, Blatt, & Flanigan, 2011; Rivera-Royero, Galindo, & Yie-Pinedo, 2016). The multi-objective deterministic model by Lin et al. (2011) distributes prioritized aid, minimizing unmet demand, logistics costs, and differences in the satisfaction rate between affected areas. Ferrer et al. (2016) addressed last-mile distribution under uncertain conditions using a deterministic model and a multi-criteria metaheuristic approach. Rivera-Royero et al. (2016) minimizes a deprivation cost to mitigate unmet demand in a post-disaster situation, as discussed next. All the aforementioned papers did not discuss the useful impact of performing the existing two types of multiple trips towards to save overall resources. Here, we explicitly show that allowing a vehicle to make several journeys within the period and over the time horizon without restricting the period's length helps to save overall resources.

Recent years have seen an emphasis on addressing human suffering in humanitarian logistics. Holguín-Veras et al. (2013) distinguished between social costs (deprivation plus logistics costs) and other objectives while a later paper Holguín-Veras et al. (2016) discussed how to estimate deprivation functions. Most research has considered deprivation costs within relief distribution models, such as Pérez-Rodríguez and Holguín-Veras (2015) and Rivera-Royero et al. (2016) who both integrate distribution of supplies and fleet sizing with inventory allocation decisions, but without explicitly considering facility location. In particular, Pérez-Rodríguez and Holguín-Veras (2015) incorporated social costs as a sum of logistics and deprivation costs in mixed-integer non-linear programming models in which an exponential function accounts for the deprivation times for each demand node and emergency