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An approximation approach to a trade-off among efficiency, efficacy, and balance for relief pre-positioning in disaster management

Mohammad Rezaei-Malek [a,b,*], Reza Tavakkoli-Moghaddam [a,b], Naoufel Cheikhrouhou [c], Alireza Taheri-Moghaddam [b]

[a] School of Industrial Engineering and Center of Excellence for Intelligence Based Experimental Mechanics, College of Engineering, University of Tehran, Tehran, Iran
[b] LCFC, Arts et Métiers ParisTech, 57070 Metz, France
[c] Haute école de gestion de Genève, University of Applied Sciences Western Switzerland, 1227 Geneva, Switzerland

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ABSTRACT

This work develops a multi-objective, two-stage stochastic, non-linear, and mixed-integer mathematical model for relief pre-positioning in disaster management. Improved imbalance and efficacy measures are incorporated into the model based on a new utility level of the delivered relief commodities. This model considers the usage possibility of a set of alternative routes for each of the applied transportation modes and consequently improves the network reliability. An integrated separable programming-augmented ε-constraint approach is proposed to address the problem. The best Pareto-optimal solution is selected by PROMETHEE-II. The theoretical improvements of the presented approach are validated by experiments and a real case study.

1. Introduction

In 2013, natural disasters killed 21,610 persons, made 96.5 million victims, and caused around US$ 156.7 billion worth of damages (Guha-Sapir et al., 2014). Disaster management approaches can help to mitigate the impacts on humans' lives on the basis of the development of adapted Humanitarian Relief Logistics (HRL) networks (Galindo and Batta, 2013). The Fritz Institute defines HRL as "the process of planning, implementing and controlling the effective, cost-efficient flow and storage of goods and materials as well as related information, from the point of origin to the point of consumption for the purpose of meeting the end beneficiary's requirements" (Thomas and Mizushima, 2005). There are some important tasks that fall under the broad umbrella of the HRL operations, e.g. preparedness, planning, procurement, transport, warehousing, tracking and tracing, and customs clearance (Thomas and Mizushima, 2005).

The HRL research is dedicated to the three planning stages in the disaster lifecycle: preparedness/pre-disaster phase, response and recovery phases (Özdamar and Ertem, 2015). Özdamar and Ertem (2015) presented a comprehensive literature review on the models, solutions and enabling technologies at the response and recovery phases.

* Corresponding author at: School of Industrial Engineering and Center of Excellence for Intelligence Based Experimental Mechanics, College of Engineering, University of Tehran, Tehran, Iran.

E-mail addresses: mohammad.rezaeimalek@ensam.eu (M. Rezaei-Malek), reza.tavakkolimoghaddam@ensam.eu (R. Tavakkoli-Moghaddam), naoufel.cheikhrouhou@hesge.ch (N. Cheikhrouhou), taherimoghadam@ut.ac.ir (A. Taheri-Moghaddam).

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At the preparedness phase, which is the domain of this work, various strategic decisions and procedures are devised before a disaster really occurs. For instance, the decisions about the number and locations of main Distribution Centers (DCs) to be opened and the amount of Relief Commodities (RCs) (e.g., non-perishable foods, medical supplies, clothes, blankets and tents) to be pre-positioned (Ahmadi et al., 2015). In fact, RCs can be secured or even purchased and pre-positioned at the preparedness phase (Altay and Green III, 2006). Humanitarian organizations can improve the agility of the HRL operations and appropriately respond to emergency situations if they establish a pre-determined network in which the location and required quantity of RCs are decided in advance that a disaster occurs (Rawls and Turnquist, 2010). The aforementioned problem is known as Location with Relief Distribution and Stock Pre-positioning (LRDSP) problem in the HRL literature (Caunhye et al., 2012).

The initial studies that dealt with the relief pre-positioning problem in disaster management were about oil spills (e.g., see Psaraftis et al. (1986), Wilhelm and Srinivasa (1996), and Iakovou et al. (1997)). Later, Akkihal (2004) addressed the relief pre-positioning problem in humanitarian and disaster relief management through a facility location approach. His work concentrated on determining locations that optimize worldwide humanitarian operations. He developed a methodology, which applies integer programming to minimize the distance from warehouses to people who are likely to require humanitarian aid. After Akkihal (2004), many researchers have dealt with the relief pre-positioning problem. In this regard, Caunhye et al. (2012) reviewed the literature of emergency optimization models. They explored some of the papers that considered the LRDSP problem. In addition, Hoyos et al. (2015) surveyed the published papers in the LRDSP category dealing with inherent uncertainty of the disaster area by stochastic components. These optimization models concurrently determine the optimal decisions on facility location, relief distribution and stock pre-positioning.

Jia et al. (2007) proposed a maximal-covering location model for the LRDSP problem. As extension of this work, Balcik and Beamon (2008) determined not only the number and locations of DCs, but also the quantity of pre-positioned RCs at each DC. The MILP model attempted to maximize the total expected demand covered by the established DCs (as a measure of efficacy), while capturing budgetary, capacity and response time restrictions. They addressed the uncertainty of the demand of DPs by a scenario-based approach.

Rawls and Turnquist (2010) coped with the LRDSP problem by a location-allocation approach and proposed a two-stage stochastic, mixed-integer program to minimize the expected costs over all scenarios while capturing facility capacity restrictions. They considered the uncertainties about undamaged amounts of the stocked RCs and capacity of the transportation network by a scenario-based approach. The costs were related to the selection of locations and sizes of facilities, RC acquisition and stocking, shipment of RCs to DPs (as measures of efficiency), unsatisfied demand penalties and holding costs for unused RCs (as measures of efficacy). Mete and Zabinsky (2010) developed a two-stage stochastic program for the storage and distribution problem of Medical Supplies (MSs) in disaster management. They incorporated a restriction into the model to assure that the amount of unmet demand at each hospital cannot exceed a predefined threshold. The objective function of the model was to minimize the total cost of operating warehouses (as a measure of efficiency), and the expected value of total transportation duration and the penalty of unfulfilled demand (as measures of efficacy) with respect to predetermined disaster scenarios. They handle the uncertainty of required time to transport MSs to the hospitals using a scenario-based approach.

Regarding the consideration of the different kinds of natural disasters (i.e., flood and earthquake) and their relief requirements, Duran et al. (2011) developed a model to evaluate the effect of pre-positioning RCs on the CARE organization's average relief-aid emergency response time. The proposed MILP model captured the constraints about facility capacity, supply, demand and number of warehouses to be opened, and took account the uncertainty of number of people affected and their demand under different demand instances regarding the different disaster types. They considered the average of the weighted response times (as a measure of efficacy) to be minimized over the demand instances, while the former studies attempted to design a more cost-efficient network.

Rawls and Turnquist (2011) defined a reliable set of scenarios and added some constraints to ensure a certain level of service quality in the selected scenarios as parts of the reliability set. Rawls and Turnquist (2012) extended their previous papers to present a dynamic allocation model for optimizing the preparedness planning. The considered uncertainties were related to demands and their locations.

Döyen et al. (2012) presented a two-echelon, two-stage stochastic programming model for the LRDSP problem, where decisions were made to determine the location of regional and local rescue centers, the amount of RCs to be kept at the pre-disaster regional rescue centers, and the amount of RCs flows at each echelon.

A robust two-stage stochastic approach was developed by Bozorgi-Amiri et al. (2013) for a multi-objective disaster relief logistics network to determine the location of DCs and RCs allocation while capturing the facility capacity restrictions. In addition, minimization of the sum of maximum shortage at DPs (as a measure of efficacy) was considered as the second objective function of their model. Barzinpour and Esmaeili (2014) contributed to the literature by using the Proactive damage estimation result of Risk Assessment tool for Diagnosis of Urban Areas against Seismic Disaster software as an input to assign the affected people to local facilities that should be opened.

Rezaei-Malek and Tavakkoli-Moghaddam (2014) developed a robust bi-objective mixed-integer mathematical model for HRL network planning. They simultaneously considered minimization of the average weighted response time (as a measure of efficacy) and the total cost (as a measure of efficacy) as the objective functions. In the same year, Garrido et al. (2014) assumed there are different RCs needed different types of transportation modes to be delivered to DPs. For instance, medications may need reefer vehicles while fresh water needs tankers. Therefore, they considered different vehicles' classes so