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Innovative Applications of O.R.

Designing humanitarian supply chains by incorporating actual post-disaster decisions

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A R T I C L E I N F O

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A B S T R A C T

Existing models for disaster preparedness and response address network design and resource allocation challenges. However, these models typically adopt a global optimization point of view, which may not be attainable since they do not consider the actual decision-making process after a disaster occurs. This process is based mostly on practitioners' knowledge and experience, rules of thumb and the population behavior. In this paper, we develop a new mathematical model that incorporates such practical considerations. The model includes actual post-disaster decisions through a set of "humanitarian constraints". We then present an efficient optimal solution method to solve small/medium-size instances of the resulting problem and a heuristic algorithm based on the Tabu-search method for large instances of the problem. We test our methods on problems with randomly generated data, as well as real data obtained from the Geophysical Institute of Israel. The results demonstrate that our heuristic performs exceptionally well, and optimal solutions are obtained in almost all cases. More importantly, we show that ignoring the actual decision-making process that occurs at the post-disaster stage results in inferior actual overall solutions. Using the humanitarian constraints improves the entire supply chain performance. Therefore, it is critical to accurately incorporate post-disaster decisions during the pre-disaster planning phase.

1. Introduction and literature review

On April 2015, during our work on this research, Nepal was hit by an earthquake. The earthquake, with a magnitude of 7.8 moment magnitude, killed more than 9000 people, injured more than 23,000 people, left thousands of people homeless and caused billions of dollars in damage. Unfortunately, Nepal's earthquake was not an exception but rather yet another addition to the long list of disasters that have affected our planet and its inhabitants over the past couple of decades. According to the Emergency Event Database (EM-DAT, www.emdat.be), 11,495 natural disasters occurred worldwide between 1980 and 2015, with more than 6 billion people affected, more than 135 million left homeless, over 2.5 million deaths, and reported damage valued at US$2.71 trillion. The major disasters in recent years include the tsunami in South Asia (2004); Hurricane Katrina in the US (2005); and earthquakes in Pakistan (2005), Java (Indonesia) (2006) and Japan (2011). Although these events could not have been avoided, their impact could have been reduced by improving the preparation and response efforts. This paper addresses supply chain decisions that can enhance the impact of relief operations in humanitarian situations caused by disasters such as Nepal's earthquake, as well as other crises, such as floods, storms, and wars.

Strategies that aim to provide humanitarian relief for natural or man-made disasters, under high uncertainty and limited availability of resources and infrastructure, are applied at different time stages. The first stage, pre-disaster, consists of mitigation and preparedness operations. Important decisions in disaster preparedness include locating emergency warehouses and pre-positioning inventory there that can be used to provide an initial response to affected areas during the first critical hours. Providing this response will occur in the next stage, the post-disaster stage, which will additionally include decisions about opening local facilities to serve the affected population. The last stage includes recovery operations, such as cleaning debris and reestablishing damaged communities. In this paper, we address decisions that pertain to the first two stages, focusing on the interactions between them. The goal of this research is to determine the humanitarian supply chain structure and inventory allocation rules, while incorporating in our model *actual post-disaster decisions*. That means, decisions that are made by the aid providers and the beneficiaries in practice, after the occurrence of a disaster, reflecting their behavior. These decisions are described in detail in the model description in Section 2.2.

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The contributions of this paper are as follows: First, we develop and analyze a mathematical model that incorporates actual post-disaster decisions implemented by aid providers and beneficiaries, i.e., decisions that mimic their behavior in practice. Second, we develop efficient solution methods to solve the resulting problem. For small/medium-size instances of the problem, we present an efficient optimal solution method and for large instances, we develop a heuristic algorithm, based on the Tabu-search method, which is shown to perform exceptionally well. Finally, we perform an experimental study in which we explore and provide insights on how incorporating decision making at a later stage affects design decisions made in an earlier stage. We conclude from this study that by implementing our research results, the efficiency and effectiveness of pre-disaster planning and execution can be improved, leading to more lives saved and better aid and support provided to disaster survivors. In the rest of this section, we review the literature on Humanitarian Logistics (HL) models, and their relationship to our work.

The supply chain problems that arise during the pre-disaster and post-disaster stages resemble the well-known facility location problem combined with assignment/transportation considerations, see, for example, Klose and Andreas (2005). Specifically, a set of facilities has to be selected from a larger set of potential facilities; each demand point needs to be assigned to one of the open facilities, from which it receives its demand. The objective function, to be minimized, includes the fixed cost of opening the facilities, as well as the variable transportation costs for each pair of demand point and its associated facility.

In the HL stream of research, there are similar models that are designed to determine where to locate emergency warehouses/facilities, from which supply will be sent to demand points that are hit by a disaster. Some unique features that distinguish these models from those of commercial supply chains are a modified objective function and/or constraints. Balcik and Beamon (2008) introduce a model that combines decisions regarding facility locations with stock pre-positioning for humanitarian relief. They use an objective function that maximizes the total expected demand covered by the established distribution centers under pre- and post-disaster budget constraints. Duran, Gutierrez, and Keskinocak (2011) minimize the expected average response time to demand points under budgetary constraints. Collaborating with CARE International (a large humanitarian organization), they developed a mixed-integer linear programming model that finds the optimal network configuration (facility location, stored relief items and inventory levels). Rawls and Turnquist (2010) use an objective function that minimizes the costs of opening facilities, purchasing, and transportation, as well as penalty and holding costs. However, they consider special constraints that are unique to a humanitarian environment, such as uncertainty regarding the survival of the pre-positioned stock and the condition of the transportation network. Salmerón and Apte (2010) minimize the expected casualties from critical and stay-back populations as well as the expected unmet transfer of population. Bozorgi-Amiri, Jabalameli, and Mirzapour Al-e-Hashem (2013) consider a multi-objective function that aims to minimize the expected total costs, cost variability and expected penalty while maximizing demand satisfaction. Holguín-Veras, Pérez, Jaller, Van Wassenhove, and Aros-Vera (2013), claim that the objective function is a fundamental component in deciding how to harmonize conflicting goals and allocate scarce resources optimally, and suggest the use of social costs, which include logistical and deprivation costs. Kılcı, Kara, and Bozkaya (2015) proposed MILP to select locations for temporary shelter sites. They maximize the sum of the weights of the selected facilities, according to a weight function, which evaluates the attractiveness of each facility.

In the above facility location models, as in most of the existing humanitarian facility location models, the supply chain consists of a single echelon. Döyen, Aras, and Barbarosoğlu (2012) consider a two-echelon relief supply chain, consisting of regional and local rescue centers. In the pre-disaster stage, decisions are made about the location of the regional rescue centers and the quantity of items stored in them. In the post-disaster stage, decisions are made regarding the local rescue center locations, the assignment of the demand points to these centers, the flow amounts at both echelons, and the level of shortages. Their objective is to minimize the total costs associated with establishing the facilities, transportation, and inventory. Tofighi, Torabi, and Mansouri (2016) address a two-echelon humanitarian logistic network, similar to Döyen et al. (2012), and propose a two-stage fuzzy stochastic model for prepositioning and distribution of relief commodities while considering the inherent uncertainty of demand and transportation time. Their objective function minimizes costs and distribution times. Khayal, Pradhananga, Pokharel, and Mutlu (2015) also considered a two-echelon supply chain in a dynamic periodic model, which consists of a single central Supply Point (SP) and Temporary Distribution Centers (TDCs) that may vary from period to period. Pradhananga, Mutlu, Pokharel, Holguín-Veras, and Seth (2016) consider a supply network that consists of multiple SPs and demand points, which can be selected for inventory prepositioning in addition to the SPs. Both Khayal et al. and Pradhananga et al. use an objective function that aims to minimize the total social costs, as suggested by Holguín-Veras et al. (2013). A real life example for such a distribution network can be found in Holguín-Veras et al. (2014), that describe a three-echelon network that was operated after the cascading disaster at the Tohoku region in the 2011 Japan earthquake. The network included distribution centers (DCs) both at the top and at the middle layer of the supply chain and Refuge centers (RCs) at the bottom.

Balcik, Beamon, and Smilowitz (2008) study a supply chain structure similar to the one presented in Döyen et al. (2012) and Tofighi et al. (2016) but do not consider facility location decisions. Rather, they assume that the location of the Local Distribution Centers (LDCs) is pre-determined and address the last mile distribution problem, i.e., the distribution of supplies from LDCs to demand points. In their model, they assume that supplies are allocated proportionally among demand points based on demand realizations and population vulnerabilities. In other words, they balance the weighted (by vulnerabilities) unsatisfied demand among all demand points. This assumption is justified by claiming that in practice, allocation decisions are frequently made while considering the relative vulnerabilities of aid recipients and that the minimum standards to be attained in disaster assistance determined by the Sphere Project (2004) require that relief aid distribution be fair and equitable. They present a two-phase modeling approach for minimizing routing and penalty costs. Noyan, Balcik, and Atatkan (2016) study the Stochastic Last Mile Relief Network Design Problem (SLMRND), which determines the locations and capacities of PODs (points of distribution) to be located in the last mile network, assigns demand locations to the PODs, and allocates available supplies among the PODs while considering the uncertainty in post-disaster relief demand and transportation network conditions. They characterize the concepts of accessibility and equity within the context of last mile distribution and present a mathematical model that incorporates them while capturing the uncertain aspects of the post-disaster environment. Their objective function maximizes the expected total accessibility, which is defined as the "ease of access to the PODs/relief supplies". We note that the relief distribution models of Balcik et al. (2008) and Noyan et al. (2016) are used for post-disaster planning and focus on the last mile supply distribution.