Computers & Industrial Engineering 91 (2016) 229–238

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

An integrated resource allocation and distribution model for pre-disaster planning

Rojee Pradhananga [a], Fatih Mutlu [a,*], Shaligram Pokharel [a], José Holguín-Veras [b], Dinesh Seth [a]

[a] Department of Mechanical and Industrial Engineering, College of Engineering, Qatar University, 2713 Doha, Qatar

[b] Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, JEC 4030, 110 8th Street, Troy, NY 12180, USA

ARTICLE INFO

Article history:
Received 14 October 2014
Received in revised form 9 November 2015
Accepted 11 November 2015
Available online 1 December 2015

Keywords:
Emergency logistics
Resource allocation
Critical supplies prepositioning
Social cost

ABSTRACT

In this paper, a three-echelon network model is proposed for integrated emergency preparedness and response planning for the distribution of emergency supplies. The model minimizes the social cost to identify a set of potential supply points (SPs) at the highest echelon, where supply items are consolidated and sent to the prepositioning facilities. The sum of logistics and deprivation costs incurred by the population due to the lack of access to goods or services, is considered as the social cost in this model. The deprivation cost is assumed to increase exponentially with the deprivation time. The model also considers pre-disaster and post-disaster purchasing decisions at the SPs, and allows direct shipments from SPs and prepositioned facilities to the demand points. Numerical analysis shows that multiple supply sources can ensure efficient distribution of the supplies and reduce the deprivation costs. The results also indicate that partial prepositioning and post-disaster purchasing can reduce the shortage in emergency supplies.

1. Introduction

Large-scale natural disasters such as hurricanes, tornados, and floods can affect many cities and millions of people. In the aftermath of such disasters, providing immediate emergency supplies (such as water, food, blankets, or tents) is one of the most critical tasks. These supplies are vital, and should be delivered to the affected people at the earliest possible time. This is possible only if a careful integration of preparedness planning and response planning is adopted. The preparedness planning includes a distribution network structure, and provisioning and prepositioning of supplies. The response planning includes the delivery of supplies to the demand points, and purchasing of extra supplies in case of deficits.

In this paper, an integrated planning model is proposed for providing emergency supplies to people in a large region affected by a disaster. The overall objective is to deliver supplies to the disaster victims in a timely and cost-effective manner by minimizing the social cost. The social cost concept includes the logistics cost and the deprivation cost. The notion of deprivation cost is derived from welfare economics to represent the suffering of the disaster-affected individuals who are deprived of emergency supplies (Holguín-Veras, Pérez, Jaller, Van Wassenhove, & Aros-Vera, 2013).

The provision of emergency supplies and their prepositioning at facilities near potential disaster areas enable faster response (Rawls & Turnquist, 2011) and a reduction in distribution costs (Ergun, Karakus, Keskinocak, Swann, & Villarreal, 2010). Holguín-Veras, Pérez, Ukkusuri, Wachtendorf, and Brown (2007) mention that there was a significant delay in disaster response in the case of Hurricane Katrina (in August 2005) due to inefficient prepositioning of critical resources. The pre-positioned resources were significantly fewer than the actual demands, and were stored too far away from the affected areas (U.S. House of Representatives, 2006). Based on this experience, United States Federal Emergency Management Agency (FEMA) pre-positioned 95 truckloads of food, 165 truckloads of ice, and 185 truckloads of water in preparation for Hurricane Rita, which occurred in September 2005. A good prepositioning helped significantly improve the disaster response.

The remainder of the paper is as follows. Literature review on the models developed for preparedness planning and response planning is given in Section 1.1, followed by the objectives and contribution to the research. In Section 2, the proposed model is discussed and developed. Numerical and sensitivity analysis are given in Section 3, and conclusions are given in Section 4. Potential future research directions are also discussed in Section 4.

* Corresponding author.

http://dx.doi.org/10.1016/j.cie.2015.11.010
0360-8352/© 2015 Elsevier Ltd. All rights reserved.

1.1. Literature review

The analytical studies on preparedness and response decisions typically employ a stochastic model due to the uncertainties in the scale of impact following a disaster. The multi-period planning method has been suggested as an alternative strategy to deal with the uncertainties (Hoyos, Morales, & Akhavan-Tabatabaei, 2015). However, this type of planning methodology is suitable mainly for the last stage distribution (e.g., Rottkemper, Fischer, & Blecken, 2012; Sheu, 2007; Yi & Özdamar, 2007; Özdamar, Ekinci, & Küçükyazici, 2004), and has limited applicability in preparedness planning.

Majority of the literature (e.g., Barbarosoğlu & Arda, 2004; Balcik & Beamon, 2008; Chang, Tseng, & Chen, 2007; Davis, Samanlioglu, Qu, & Root, 2013; Lodree, Ballard, & Song, 2012; Mete & Zabinsky, 2010; Rawls & Turnquist, 2010; Rawls & Turnquist, 2011; Salmerón & Apte, 2010) in preparedness and response planning use scenario-based stochastic formulations. Campbell and Jones (2011) employ a risk-based cost model as an alternative to scenario based model.

The scenario-based formulation considers several disaster scenarios each with a probability of occurrence, determined based on the historical records of similar events in the area (for details, refer to Barbarosoğlu & Arda, 2004). Use of scenarios in distribution problems is justified due to its simplicity in understanding and model development. With the exception of a few models, e.g., the maximum covering model proposed by Balcik and Beamon (2008), scenario-based models predominantly are two-stage models.

Several scenario-based two stage models (e.g., Salmerón & Apte, 2010) have objective of service maximization, for which the service level is considered as the percentage of satisfied demand of emergency supplies and/or avoided casualties. On the other hand, a great majority of the two stage models have cost minimization objective (Barbarosoğlu & Arda, 2004; Chang et al., 2007; Davis et al., 2013; Lodree et al., 2012; Mete & Zabinsky, 2010; Rawls & Turnquist, 2010; Rawls & Turnquist, 2011). In these models, scenarios are used to describe the demand at various zones in the disaster area. In addition, Rawls and Turnquist (2010) and Rawls and Turnquist (2011) consider the potential damages to the transportation network and the quantities for prepositioning in each scenario.

Among the studies that employed scenario-based two stage formulations with cost objective, only a few of them consider fixed locations for prepositioning the emergency supplies (e.g., Barbarosoğlu & Arda, 2004; Davis et al., 2013; Lodree et al., 2012); but a great majority of the studies suggest jointly optimizing the facility location and prepositioning of emergency supplies, because the location of such facilities can significantly affect the post-disaster distribution of the supplies (Chang et al., 2007; Mete & Zabinsky, 2010; Rawls & Turnquist, 2010; Rawls & Turnquist, 2011).

The existing two stage models in emergency logistics literature have overlooked three important aspects. The first aspect is the distribution network structure. Majority of the models have a two-tier distribution network in which resources are distributed through certain selected prepositioning facilities. For disasters that affect very large areas, for instance, hurricanes such as Katrina, it is fairly difficult to consider a centralized preparedness with only the prepositioned facilities involved in the post-disaster distribution. It is more practical to consider a multi-echelon network, in which supplies are consolidated at a number of supply points (SPs), and then distributed to the prepositioning facilities. This type of arrangement would enable direct shipments from the SPs to the demand points in the post-disaster stage as well.

The second aspect is the consideration of deprivation costs. The existing two stage models typically consider constant deprivation cost such as shortage cost and ignore the cost of supply deprivation associated with the post-disaster distribution. Rottkemper et al. (2012) proposed a linear penalty cost function that increases with delays in demand satisfaction. Such a consideration provides a better representation of deprivation cost than the models considering constant cost (Holguín-Veras et al., 2013). However, in post-disaster situations, deprivation follows an exponentially increasing non-linear function (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012; Holguín-Veras et al., 2013; Pérez & Holguín-Veras, 2015). This is to note that there could be delays in the delivery of supplies to the SPs due to congestion in the transportation routes (Pratap, Nayak, Cheikhrouhou, & Tiwari, 2015) or limited unloading capacities at the SPs (Pratap, Daultani, Tiwari, & Mahanty, 2015). Such situations can also increase the level of deprivation. However, this research assumes no such supply restrictions and capacity constraints.

The third aspect is the relevance of partial prepositioning and extra purchasing in post-disaster stage. A few of the models (Barbarosoğlu & Arda, 2004; Davis et al., 2013) implicitly consider partial prepositioning of the supplies but majority of the models do not consider the purchasing decisions. Operational strategies such as extra purchasing in pre-disaster stage and keeping some of the supplies at the safer place, and purchasing in the post-disaster stage have not been well studied.

1.2. Contributions

In this paper, the above mentioned aspects are addressed in the following manner: First, a three-echelon network model is used with a set of potential SPs at the upper echelon. The potential SPs are typically large facilities in and around the potential disaster region where supply items can be consolidated for prepositioning. Multiple supply sources are considered to overcome the supply disruption problem that can happen with single sourcing. The model also allows direct shipments from SPs to the demand points.

Second, in the model social cost (the sum of logistics costs and deprivation costs) minimization approach is used. Unlike the constant and linear deprivation cost, the model considers a deprivation cost function that increases exponentially with the delays in the delivery of the emergency supplies following Holguín-Veras et al. (2013).

Finally, purchasing decisions are considered both in pre-disaster and post-disaster stage. The model provides flexibility of partial prepositioning of the purchased supplies in the pre-disaster stage. In post-disaster stage, it provides limited opportunities for purchasing at the SPs since purchasing must be done in a short and chaotic period. In summary, the proposed model, compared to the existing two-stage models in the literature, is characterized by three distinct features (a) a three tier network structure with multiple SPs (b) a non-linear deprivation cost function and (c) flexibility in purchasing and prepositioning decisions.

In order to incorporate the above aspects, a scenario-based two-stage stochastic programming formulation is proposed. The scenario-based approach also considers potential network damages and differentiates itself with other models as mentioned in Table 1.

Therefore the contribution of the paper lies mainly in following two aspects:

(i) It presents an integrated location, resource allocation and distribution model for integrated preparedness and response planning, which considers a realistic network structure and deprivation cost. It provides flexibility in operational decisions such as in allocations, prepositioning, and purchasing. In this regard, this study provides the most comprehensive and, at the same time, flexible model in the two-stage scenario based preparedness and response planning literature.