Socio-Economic Planning Sciences 46 (2012) 98–109

Contents lists available at SciVerse ScienceDirect

Socio-Economic Planning Sciences

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

A transshipment model for distribution and inventory relocation under uncertainty in humanitarian operations

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ARTICLE INFO

Article history:
Available online 19 October 2011

Keywords:
Inventory relocation
Transshipment model
Disruption management
Relief item distribution
Humanitarian logistics

ABSTRACT

The number of disasters and humanitarian crises which trigger humanitarian operations is ever-expanding. Unforeseen incidents frequently occur in the aftermath of a disaster, when humanitarian organizations are already in action. These incidents can lead to sudden changes in demand. As fast delivery of relief items to the affected regions is crucial, the obvious reaction would be to deliver them from neighbouring regions. Yet, this may incur future shortages in those regions as well. Hence, an integrated relocation and distribution planning approach is required, considering current demand and possible future developments.

For this situation, a mixed-integer programming model is developed containing two objectives: minimization of unsatisfied demand and minimization of operational costs. The model is solved by a rolling horizon solution method. To model uncertainty, demand is split into certain demand which is known, and uncertain demand which occurs with a specific probability. Periodically increasing penalty costs are introduced for the unsatisfied certain and uncertain demand. A sensitivity analysis of the penalty costs for unsatisfied uncertain demand is accomplished to study the trade-off between demand satisfaction and logistical costs. The results for an example case show that unsatisfied demand can be significantly reduced, while operational costs increase only slightly.

1. Introduction

The effects of natural and man-made disasters are tremendous and devastating. In 2008 alone, 240,500 people lost their lives due to natural and man-made disasters [1]. This number does not even include the so-called “forgotten humanitarian crises”, which are not reported widely in the media although a multitude of people are affected by them. “Civilians attacked, bombed, and cut off from aid in Pakistan, Somalia, Yemen, Sri Lanka, Afghanistan, and the Democratic Republic of Congo, along with stagnant funding for treating HIV/AIDS and ongoing neglect of other diseases”, are mentioned by the humanitarian organization Médecins Sans Frontières (MSF) as some of these forgotten crises [2].

More than 90% of the disaster- and crisis-affected people live in developing countries which usually cannot provide sufficient help themselves [3]. Therefore, international organizations assist with various kinds of aid programmes. They offer, e.g., medical support, nutrition, shelter, and hygiene/sanitation services [4]. In order to provide these goods and services to the affected regions, and to be able to quickly respond in case of emergencies, an efficient and flexible supply network is necessary. However, as the fraction of logistics and supply chain activities is estimated to be up to 80% of total relief efforts, it is also important to control the logistics related costs. Therefore, humanitarian organizations increasingly reorganize their logistics strategies [5].

As the benefits which operations research (OR) methods generate in traditional logistics applications are large, the application of OR methods has also been suggested for humanitarian operations. OR methods have already been proven to be beneficial for different planning situations, mainly during the preparation and the response phase of the disaster life cycle (see Section 2 below) [6]. Meanwhile, applications of OR methods to sustained humanitarian operations are scarce [7], and this is the type of problem considered in this work.

As an example, Burundi, one of the poorest countries in the world, is considered. Burundi is a country in central Africa with a weakened economy, a deteriorated health system, and a partially destroyed infrastructure due to a long period of civil war. Eighty percent of the population in Burundi live below the poverty line, and 50% of the children under the age of five suffer from chronic malnutrition. The infant mortality rate is around 10% [8]. One of the

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0038-0121/$ – see front matter
doi:10.1016/j.seps.2011.09.003

main causes of children's deaths is malaria [9]. In order to reduce malaria mortality, patients are usually treated promptly with an Artemisinin Combination Therapy (ACT) which is provided by private and governmental facilities as well as by humanitarian organizations [10].

In this paper, the outbreak of a malaria epidemic in a certain province (resulting in a surge of demand for ACT) during sustained humanitarian operations, which have been established to improve the health care situation in the disaster-affected region, is considered. This situation requires a rapid response. Due to the fact that humanitarian activities are already taking place in the region, a number of regional depots for the distribution of goods already exist. As malaria is endemic in many areas of Burundi [11], ACT is in stock at least in limited amounts. However, the amounts which are locally stored are not sufficient to serve all people affected by the malaria epidemic. Relocation, e.g. from neighbouring depots, is hence required and reorders of ACT from a central depot may become necessary. At the same time, shortages at other depots should be avoided, as the epidemic may spread into other regions as well. Therefore, demand uncertainty in future periods and the possibility not to satisfy all existing demand have to be taken into account when developing a relocation and distribution planning approach for this situation. Below, a quantitative model for stock relocation of a specific relief item, i.e. ACT, over a specified time horizon will be developed incorporating these aspects.

Similar situations in which demand may suddenly increase or a disruption can lead to a shortage in supply, also occur in other settings in the humanitarian context: When a new disaster, e.g. an aftershock, strikes while humanitarian operations in response to a preceding earthquake are still going on; when a regional depot for relief items is broken into and items are stolen; or when lead times from a global depot are prolonged due to a deterioration of transportation conditions. All these incidents lead to planning situations which have similar characteristics as the one described above: It is necessary to relocate the available relief items such that as many beneficiaries as possible can be served within the temporal, spatial and financial restrictions.

Two objectives have to be taken into account when solving such a relocation problem: first, the minimization of unsatisfied demand, in order to make sure that as many people as possible are served, and second, the minimization of total transportation and inventory holding costs. Especially in case of forgotten humanitarian crises, funding is scarce and therefore a cost-efficient solution becomes more important than in the initial disaster response phase, when media reports lead to high attention and larger amounts of donations [2].

The purpose of this work is to develop a model and a solution method to solve this multi-objective multi-period planning problem. In order to achieve this aim, the use of penalty costs for unsatisfied demand is suggested for combining the two objectives. Moreover, as the planning horizon consists of more than one period, and as the effects of a shortage in supply tend to get worse the longer the affected regions remain unserved, penalty cost parameters are used that increase with every period for which demand has been unsatisfied. To include new information arising during the relief operation, a rolling horizon solution approach is developed which solves the model repeatedly for each period of the planning horizon.

To the knowledge of the authors, the approach suggested here is a new contribution to the field of disaster planning and logistics. It supports decision making during disaster relief efforts and emergency interventions by enabling effective relocation of inventory and reorganization of transportation plans, depending on new developments and on information becoming available during the relief action.

The remainder of the paper is structured as follows: In the next section, an overview of the relevant literature in inventory and transportation planning for disaster relief, humanitarian operations and in related fields is presented. In Section 3, the new inventory relocation model is presented, and the solution method is described. Thereupon, the situation which is considered as an example case is described in more detail, and the data which are used to evaluate the new model are introduced in Section 4. In Section 5, computational results are presented and interpreted. A short discussion concludes this paper.

2. Literature review

Logistics and, more comprehensively, supply chain management is of major importance in humanitarian operations [5,6]. During the past decade an increasing number of papers has been published in this field, covering a variety of planning problems. Various applications of OR methods to logistical problems have been suggested, as e.g. approaches for facility location planning for humanitarian service facilities during the disaster preparation phase, e.g. [12,13], and vehicle routing methods for planning distribution tours in regions that have been hit by a disaster, mostly directed at the immediate response phase, e.g. [14,15].

Inventory decisions in combination with allocation decisions are considered, e.g., by Chang et al. [16] and Balçik and Beamon [17]. The former set up stochastic location and inventory allocation models for warehouses that are to be used in an emergency response setting after a flood. The latter develop a facility location and inventory planning model for sudden-onset disasters. Models for resource allocation and inventory holding in disaster response are also formulated by Fiedrich et al. [18], Beamon and Kotleba [19], and Lodree and Taskin [20]. Beamon and Kotleba [19] develop a model for a long-term framework and take demand uncertainties into account. Lodree and Taskin [20] set up an insurance risk policy framework to determine optimal inventories for disaster relief. Fiedrich et al. [18] examine resource allocation in a disaster response setting after an earthquake.

Delivery planning in humanitarian operations is an aspect that has been studied rather extensively. As early as the 1990s, Haghani and Oh [21] develop a large-scale mixed-integer programming model for optimizing flows of commodities to the beneficiaries of a disaster relief operation. In their approach, they make use of penalty costs for unsatisfied demand. Barbarosoğlu and Arda [22], Özdamar et al. [15], and Yi and Özdamar [23] develop different transportation and network flow models, taking into account uncertainty [22], multiple commodities [23] and multiple periods [15]. The former also introduce shortage costs for unsatisfied demand. Furthermore, Rawls and Turnquist [24] and Salmerón and Apte [25] present two-stage stochastic models for relief item prepositioning, also using penalty costs to avoid unsatisfied demand. A multi-objective model for the optimal distribution of relief items, taking into account cost minimization, minimization of travel time, and maximization of satisfied demand, is suggested by Tzeng et al. [26]. Other multi-objective approaches are developed by Vitoriano et al. [27] who suggest a goal programming approach to support humanitarian organizations in aid distribution decisions and by Nolz et al. [28] who implement a genetic algorithm to determine the entire Pareto-front of a covering tour problem for relief item distribution.

In most of the above-mentioned contributions, the preparation phase or the immediate response phase of the disaster relief lifecycle [6] is addressed. Only few publications (e.g. Nolz et al. [29], Beamon and Kotleba [19]) are devoted to the recovery phase. Due to decreasing inflows of donations, cost-efficiency becomes increasingly important in this phase [30, 31, 2]. Therefore, standard