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Models for relief routing: Equity, efficiency and efficacy

Michael Huang [a], Karen Smilowitz [a,*], Burcu Balcik [b]

[a] Industrial Engineering and Management Sciences, Northwestern University 2145 Sheridan Road, Evanston, IL 60208, USA
[b] Industrial Engineering Department, Kadir Has University, Cibali, Istanbul 34083, Turkey

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ABSTRACT

In humanitarian relief operations, vehicle routing and supply allocation decisions are critically important. Similar routing and allocation decisions are studied for commercial settings where efficiency, in terms of minimizing cost, is the primary objective. Humanitarian relief is complicated by the presence of multiple objectives beyond minimizing cost. Routing and allocation decisions should result in quick and sufficient distribution of relief supplies, with a focus on equitable service to all aid recipients. However, quantifying such goals can be challenging. In this paper, we define and formulate performance metrics in relief distribution. We focus on efficacy (i.e., the extent to which the goals of quick and sufficient distribution are met) and equity (i.e., the extent to which all recipients receive comparable service). We explore how efficiency, efficacy, and equity influence the structure of vehicle routes and the distribution of resources. We identify trends and routing principles for humanitarian relief based on the analytical properties of the resulting problems and a series of computational tests.

1. Introduction

Recent disasters have increased attention on the effectiveness of humanitarian aid; there is increased pressure from donors on relief agencies to show that pledged aid and goods are reaching those in need quickly (Van Wassenhove, 2006). This has led to a larger focus on improving humanitarian relief logistics. The recent large scale disasters and relief efforts (e.g., 2004 Asian tsunami, 2005 Pakistan earthquake, 2010 Haiti earthquake) highlight the need for improved logistics in the field. For example, following the Tsunami, the amount of pledged relief overwhelmed the relief agencies' ability to properly store and distribute the aid (Russell, 2005). Given the trends in the impact of disasters on vulnerable populations and economies worldwide and the criticality of logistics in humanitarian relief operations, it has been increasingly highlighted that Operations Research (OR) can help improve the logistics of humanitarian aid (Van Wassenhove, 2006).

This paper focuses on last-mile distribution in a humanitarian relief chain from a distribution center to beneficiaries (Balcik et al., 2008). Relief supplies must be delivered quickly in sufficient amounts. Given limitations in transportation resources and relief supplies, and damaged infrastructure, it is challenging to plan last mile operations (Balcik et al., 2008). Distribution decisions are often made ad hoc, which may lead to inefficient use of resources, slow response, and inadequate or inequitable relief deliveries.

The classical vehicle routing problem (VRP) minimizes total transportation costs; in humanitarian relief, one is primarily concerned with whether the routes are able to deliver the aid quickly. Focusing on relief response times, Campbell et al. (2008) show that the choice of objective affects how aid is distributed. With alternative objectives of minimizing the last arrival time and minimizing the sum of arrival times, the authors demonstrate that superior service times may be achieved

* Corresponding author. Address: 2145 Sheridan Road, TECH, M233 Evanston, IL 60208, USA. Tel.: +1 847 491 4693; fax: +1 847 491 8005.
E-mail addresses: Michael-Huang@u.northwestern.edu (M. Huang), ksmilowitz@northwestern.edu (K. Smilowitz), burcu.balcik@khas.edu.tr (B. Balcik).

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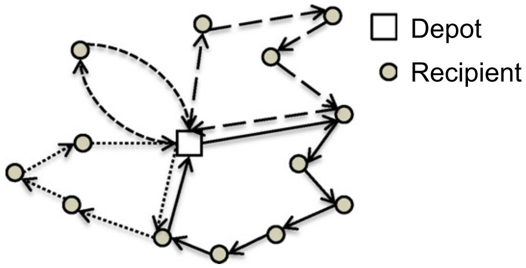

Fig. 1. A set of routes in LMDP.

than those resulting from a traditional VRP objective. They show that minimizing total routing costs results in solutions with longer response times.

Equitable aid distribution among recipients is also a critical consideration in humanitarian relief (Beamon and Balcik, 2008). However, equity may be hard to define both in practice and for modeling purposes. In this paper, we characterize equity in terms of the disparity between service levels among aid recipients, where service levels are characterized by delivery speed and amount. Even so defined, it is not clear how equity should be modeled. Furthermore, it is not obvious how different and potentially conflicting objectives of equity, efficacy and efficiency affect the route structures in the relief context.

Balcik et al. (2008) present an analysis of last mile operations and show how modeling these operations with all the associated complexities can make it difficult to study the underlying differences in route design that occur. Our goal in this paper is to simplify the modeling of last mile distribution to a more stylized setting where we can more easily gain insights into the effects of equity and other considerations in relief distribution. We refer to this problem setting as the last-mile delivery problem (LMDP). The LMDP designs vehicle routes and distribution schedules for a fleet of vehicles delivering supplies from a distribution center, yet unlike Balcik et al. (2008), we focus on a single period problem where each vehicle performs at most one trip to deliver one commodity type. Although more restricted than Balcik et al. (2008), our problem setting still captures many critical characteristics of the last mile environment; in particular, the LMDP in this paper would well address relief operations in rural areas where each vehicle can perform only one trip per period and supplies are distributed in the form of standard packages/pallets. Relief organizations often make daily distribution plans rather than considering multiple days ahead, especially during the initial phases of the emergency due to the chaotic environment and lack of reliable information (Mantyvaara, 2010). An example of LMDP routes is presented in Fig. 1. The demand of a site can be satisfied by more than one vehicle in the LMDP, similar to the Split Delivery Vehicle Routing Problem (SDVRP). The SDVRP is motivated by the potential savings in costs due to splitting demand among multiple vehicles (Dror and Trudeau, 1989). Split deliveries in last mile relief distribution can allow one to quickly serve large demands using limited resources. Our problem setting allows us to analyze the impact of different objectives on route structures and the performance of aid distribution, in terms of (i) efficiency (transportation costs), (ii) efficacy (quick and adequate response), and (iii) equity (fairness as measured by deviations between recipients in efficacy). The incorporation of equity in particular leads to unique challenges.

We develop a set partitioning model for the LMDP to incorporate alternative objectives, based on efficiency, efficacy and equity metrics. Analytical properties of the LMDP models are examined. A numerical study of small instances, in which it is possible to obtain optimal solutions for each of the objectives, is conducted to develop insights into route characteristics. Our analysis shows that there exist substantial differences among solutions that attempt to minimize efficiency compared to those that are concerned with efficacy and equity. Heuristics are developed to solve large instances of the LMDP variations.

This paper is organized as follows: in Section 2, we review the relevant literature. Section 3 gives a detailed description and analysis of the LMDP variations. Section 4 proposes heuristics for the LMDP variations. Section 5 discusses practical implications of this work and future directions.

2. Literature review

There is a growing literature that addresses relief supply distribution in humanitarian logistics. One of the earliest studies that addresses distribution of relief supplies from a distribution center to several camps is Knott (1987). The author formulates a linear programming model that finds the number of trips each vehicle makes to maximize the amount of deliveries while minimizing transportation costs and discusses how considering additional aspects might make the problem very difficult to solve. More recently, the literature addresses more complicated relief supply distribution problems and captures the inherent complexities of the humanitarian relief environment, including multiple commodities, multiple transportation modes or vehicle types, multiple periods, uncertain or varying demand and supply levels and transportation network conditions, and delivery time windows. Most studies develop heuristic algorithms to solve the proposed models (e.g., Haghani and Oh, 1996; Barbarosoglu et al., 2002; Ozdamar et al., 2004; Lin et al., 2009; Shen et al., 2009; Van Hentenryck et al., 2010) or use commercial solvers to test the models for small to moderate problem instances (e.g., Barbarosoglu and Arda, 2004;