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Modeling multiple humanitarian objectives in emergency response to large-scale disasters

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ABSTRACT

In this paper, we characterize the humanitarian objectives of emergency resource allocation and distribution in disaster response operations. We formulate the humanitarian principles as three objective functions, i.e., lifesaving utility, delay cost and fairness. An integrated multi-objective optimization model that combines resource allocation with emergency distribution is developed, where a time space network is used to incorporate the frequent information and decision updates in a rolling horizon approach. The proposed model is shown to be a convex quadratic network flow problem, for which we design an efficient Variational Inequality algorithm. Computational results are reported to illustrate the performance of the proposed model and algorithm.

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1. Introduction

In recent years, large-scale natural or man-made disasters have occurred frequently (Gad-el Hak, 2008), causing large casualties and often destroying infrastructures, e.g., electricity, transportation, and communication. How to effectively respond to unpredictable and irregular emergency events has become of primal importance worldwide. The critical issues in such extreme events are how to respond immediately and how to schedule responses that can minimize the consequences of these disasters (Kovacs and Spens, 2011). In this context, humanitarian rescue and relief has been receiving greater attention by more and more academic scholars and emergency management practitioners (Apte, 2010; Sheu, 2007b).

Humanitarian logistics is aimed at aiding people in surviving during and after a disaster. In the literature, the necessity and importance of Operations Research/Management Science (OR/MS) models in humanitarian logistics have been well recognized (Green and Kolesar, 2004). Researchers in OR/MS have successfully identified many important research problems (Altay and Green III, 2006; Wright et al., 2006; Simpson and Hancock, 2009; Caunhye et al., 2012), such as resource allocation, evacuation, and demand assessment, as well as emergency distribution. However, most existing works rely on traditional OR models, and do not address the challenging characteristics of humanitarian logistics well (Apte, 2010; Kovacs and Spens, 2009; Galindo and Batta, 2013). It is critical to develop OR/MS models that can address humanitarian objectives directly.

In this paper, we consider rescue resource allocation and emergency distribution in the response phase of a disaster, in particular during the critical 72 h time window after the disastrous event happens (Gad-el Hak, 2008). We propose a multi-objective optimization model that can capture the essential humanitarian objectives. Our work differs from most existing studies in several aspects. We distinguish the need to "save as many lives as possible" and the need to "reduce the pain

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of people waiting for supplies as quickly as possible''. We also model fairness in resource allocation. Furthermore, we propose to use a time space network and a rolling horizon approach to capture the dynamic nature of humanitarian logistics. Our model allows for arrivals of supplies and demands at different times, and the evolution of input data. The time space network approach has also been used by Yan and Shih (2009), Yan et al. (2014) and Rottkemper et al. (2011) to tackle different but related research problems. Our model not only has conceptual appeal, but also incorporates computational efficiency. The proposed model can be shown to be a convex quadratic time space network flow problem, which is well studied in Jiang et al. (2014). This makes our model especially suitable for real time decision support.

Our contributions contain three aspects. Firstly, we simultaneously characterize the humanitarian principles of lifesaving effectiveness, human suffering, and fairness in the objective function. Secondly, we link the time space network with rolling horizon approach to deal with frequent information updates in the highly volatile environment of disaster response. Thirdly, we propose an integrated model that combines the decision-making of resource allocation and distribution in humanitarian operations.

Our paper is organized as follows. In Section 2, we review the literature relevant to our study. In Section 3, we build a multi-objective optimization model for humanitarian logistics. In Section 4, we discuss the managerial implications of important model parameters. In Section 5, we present a Variational Inequality algorithm to solve the proposed model. In Section 6, we report the results of computational studies. Finally, we discuss the conclusions and suggest future research directions in Section 7.

2. Literature review

Our work is related to three research streams: the mathematical formulations of humanitarian decision criteria, the multi-objective optimization models on humanitarian relief, the methodologies of modeling dynamic decision-making over time.

Commercial and humanitarian logistics are quite different in nature (Sheu, 2007b; Apte, 2010). The decision criteria of commercial logistics are often restricted to classical economic and/or logistics measures (Beamon and Balcik, 1999), such as cost, time, and the percentage of fulfilled demand. While in humanitarian relief operations, the decisions relevant to human rescue activities must be aligned with the humanitarian principles (Hilhorst, 2005) such as: (1) the human need principle, which refers to the priority of saving human lives and alleviating human suffering to the greatest extent possible, and (2) the impartiality principle, which requires that the implementation of any action must be based solely on need, with no discrimination among populations.

To reflect the humanitarian principle, there is a large literature using an utilitarian principle of maximizing the effectiveness of lifesaving, i.e., the benefit or reward in humanitarian operations. Amongst these works, a popular approach is the *priority* approach, which allocates humanitarian relief resources through prioritizing the affected regions or populations upon the damage or injury severity, i.e., the rescue resources are allocated according to the priority list. Sheu (2007a) uses a hybrid fuzzy clustering optimization approach to determine the relief distribution priorities amongst affected-area groups, and investigates the emergency co-distribution responding to the urgent demands. This work is extended by Sheu (2010) to a demand management system, which evaluates the demands in real time based on incoming information and then continually updates the priorities among affected-area groups. Chiu and Zheng (2007) address a mass evacuation problem after no-notice disasters. They classify all evacuees into several groups with different priorities, and develop a cell-transmission-based linear programming model to determine traffic assignments amongst the prioritized groups. Another stream of research aims at maximizing the number of saved people or minimizing the number of casualties. Fiedrich et al. (2000) classify the disaster-affected areas into search-and-rescue area, stabling area and immediate rehabilitation area, and then propose a dynamic program for resource allocation to minimize the total number of fatalities among these areas. Salmeron and Apte (2010) divide the affected population into critical population, stay-back population, and transfer population in a rescue asset pre-positioning problem, and then maximize the survival rate of critical populations in the objective. Some researches use a two-stage approach, where a priority list is constructed and then used as an input to another decision problem. For example, Özdamar and Demir (2012) use a priority list to make relief distribution schedules. In the literature, there are few works studying time-varying priorities with information update besides Sheu (2007a, 2010).

The criteria to capture the social costs of shortage of rescue resources, called deprivation costs, has been systematically summarized and classified in Holguin-Veras et al. (2013). They claim that most literatures adopt proxy measures to approximate the deprivation cost that arises from non-timely emergency response due to insufficient relief resource to meet the demand surge in the aftermath of disasters. They propose the concept of deprivation cost and argue that the deprivation cost must be incorporated into the objective in humanitarian operations. Moreover, computational studies show that the proxy measures cannot approximate the deprivation cost very well. Jaller (2011) and Perez (2011) also consider deprivation cost. Jaller (2011) shows that the phenomenon of material convergence in post-disaster rescue and relief, i.e., a large number of non-priority rescue resources arrive at the same distribution location together with priority rescue resources, will incur large deprivation costs. Perez (2011) investigates the effects of deprivation costs in inventory allocation. Holguin-Veras et al. (2013) model the consequence of human suffering caused by insufficient rescue resources. Nevertheless, their formulation only considers the consequence at delivery points rather than along the whole time horizon. In practice, the consequences of human suffering should be continually accrued along with the delayed response time.

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