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Real-time relief distribution in the aftermath of disasters – A rolling horizon approach

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ABSTRACT

This paper presents a rolling horizon-based framework for real-time relief distribution in the aftermath of disasters. This framework consists of two modules. One is a state estimation and prediction module, which predicts relief demands and delivery times. The other is a relief distribution module, which solves for optimal relief distribution flows. The goal is to minimize the total time to deliver relief goods to satisfy the demand, considering uncertain data and of the risk-averse attitude of the decision-maker. A numerical example based on the large-scale earthquake that occurred on September 21, 1999 in Taiwan is presented to demonstrate the system.

1. Introduction

1.1. Background and motivation

A number of devastating natural disasters occurred over the past decades (e.g., the Indian Ocean Tsunami in 2004, Hurricane Katrina in 2005, China's Sichuan earthquake in 2008, the Haiti earthquake in 2010, the Pakistan floods in 2010, Japan's Northeast earthquake in 2011, and the Haiyan typhoon in 2013). Tens of thousands of deaths and billions of dollars of economic loss due to natural disasters signal the existence of significant problems for study by any discipline with the capabilities of reducing the impacts and improving the response to such events, and highlight the need for effective disaster operations management (DOM). Disaster operations are a set of activities that are performed before and after disaster occurrence with the goal of preventing loss of human life, reducing the disaster's impact on the economy, and returning to a state of normalcy (e.g., Altay and Green, 2006; Galindo and Batta, 2013).

Generally, the two most important intervention operations in emergency response to disasters are the search-and-rescue (SAR) of trapped people and the logistics of relief materials (e.g., Najafi et al., 2013; Yi and Özdamar, 2007). The SAR takes place during the initial phase of the emergency response to find injured and trapped people in the affected area, and transport the injured people to hospitals or emergency medical centers nearby. Relief logistics (also known as emergency logistics or humanitarian logistics) activities continue for a longer period of time as they aim to provide the necessary relief commodities to people in the affected areas.

Effective and efficient delivery of relief resources to affected people is critical to the emergency response to large-scale natural disasters and, hence, emergency logistics is receiving increasing attention from academics as well as practitioners. In particular, various operations research models and algorithms have been adopted to tackle emergency logistics problems

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(see the review articles of Altay and Green, 2006; Caunhye et al., 2012; Galindo and Batta, 2013; Manopiniwes and Irohara, 2014; Simpson and Hancock, 2009). Most previous works address the static planning problems of relief distribution, which assume that relevant input data (e.g., relief demands and delivery times) or their distributional estimates for the entire planning horizon are readily available prior to the beginning of the distribution process (i.e., the assumption of complete information). However, in reality, because of complex communication and coordination issues in the aftermath of a large-scale disaster (e.g., damage to transportation and communication systems, and involvement of many third parties and government agencies), accurate and reliable input data for the entire planning horizon are typically unavailable for planning and managing the relief distribution process (Sheu, 2010). As a result, the solutions generated using static relief distribution models based on the assumption of complete information may deviate significantly from real situations and result in poor relief logistics operations that cause severe problems, such as storage facilities overwhelmed by unwanted items, uneven and late distribution, goods not reaching to victims, and so forth. (e.g., Greve, 1999; Hogland, 2007; Russell, 2005; Ito et al., 2014) These problems are the so-called "second disasters" (Ito et al., 2014).

In contrast to the classic static relief distribution models, real-world applications of relief distribution in the aftermath of disasters need to address two important issues: evolution and quality of information. Evolution of information relates to the fact that the information available to the decision maker may change during the execution of the distribution, for example, due to updated numbers of death and injury, or closure or repair of roads. Quality of information reflects possible uncertainty of the available data; for instance, the number of deaths is only known as a range estimate of its real number. In fact, in the aftermath of a disaster, the information about its impact on the supply and demand sides is generally uncertain and is revealed gradually over time. Thus, relief distribution decisions need to account for data uncertainty and be promptly adjusted in accordance with updated real-time information. The need to address these two issues in relief distribution motivates us to study the real-time relief distribution problem. This study focuses on developing an approach that is able to incorporate and utilize real-time information in the process of relief distribution in the aftermath of large-scale natural disasters.

1.2. Literature review and research gap

The seeming randomness of disaster impacts and uniqueness of incidents require dynamic, real-time, effective, and cost-efficient solutions, making the topic of disaster emergency logistics highly suitable for operations research. Sheu (2007) defines emergency logistics as the process of planning, managing, and controlling the flow of relief resources so that the urgent needs of affected people can be delivered in time. Various mathematical programming models have been developed in the literature to deal with static and deterministic relief distribution problems, including linear programming (e.g., Sheu, 2007; Sheu and Pan, 2015), integer or mixed integer programming (e.g., Abounacer et al., 2014; Afshar and Haghani, 2012; Ozdamar and Demir, 2012; Yan and Shih, 2009; Yi and Kumar, 2007; Yi and Özdamar, 2007), and mixed integer linear programming (e.g., Ozdamar et al., 2004; Sebbah et al., 2013).

In addition, recognizing the need to account for data uncertainty in relief distribution problems, a number of studies developed stochastic programming models (e.g., Barbarosoglu and Arda, 2004; Chang et al., 2007; Mete and Zabinsky, 2010; Rachaniotis et al., 2013) or robust optimization models (e.g., Ben-Tal et al., 2011; Lu, 2013; Lu and Sheu, 2013; Najafi et al., 2013). Stochastic programming approaches represent uncertain data using discrete scenarios or continuous probability distributions, and optimize the expected value of a given objective function. On the other hand, robust optimization models represent uncertain data using ranges or intervals, and optimize an objective function in worst-case scenarios. As indicated in the literature, (e.g., Ben-Tal et al., 2011; Lu and Sheu, 2013) because of the difficulty in predicting disaster occurrence and impacts as well as a lack of historical data, probability distributions and scenario data are generally unavailable. Instead, a more practical alternative for the decision maker is to use ranges or intervals to describe uncertain data. Furthermore, to effectively alleviate the impact of a disaster on affected people, the decision maker may prefer an approach that guarantees the best performance in the worst-case to methods that optimize the expected performance.

Very few existing studies addressed the issues of evolving and uncertain information in relief distribution problems (e.g., Manopiniwes and Irohara, 2014). For instance, Wohlgemuth et al. (2012) applied the dynamic vehicle routing problem with pickups and deliveries to the last mile relief distribution context. They evaluated and highlighted the benefits of dynamic optimization in anticipating varying travel times and unknown orders in the specific environment of disaster relief. Although a number of multi-period relief distribution models were proposed in the literature (e.g., Ben-Tal et al., 2011; Najafi et al., 2013; Sheu, 2007; Yi and Özdamar, 2007), all of them still assumed that the input data in multiple periods are known to the decision maker, a priori. Sheu (2010) presented a dynamic relief-demand management model for emergency logistics operations under imperfect information conditions in large-scale natural disasters. The proposed method applied data fusion to forecast relief demand in multiple areas.

According to the literature review, in spite of the practical concerns regarding information evolution and quality, the majority of existing studies in emergency logistics focus on static and deterministic models, with few developing stochastic and robust approaches to deal with data uncertainty. Furthermore, none address the dynamic relief distribution problem, in which relief demands and delivery times vary with time. To fill this research gap, this study proposes a real-time relief distribution framework that explicitly takes into account real-time information and its uncertainty in controlling relief flows in the aftermath of a large-scale disaster.