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Robust optimization for emergency logistics planning: Risk mitigation in humanitarian relief supply chains

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ABSTRACT

This paper proposes a methodology to generate a robust logistics plan that can mitigate demand uncertainty in humanitarian relief supply chains. More specifically, we apply robust optimization (RO) for dynamically assigning emergency response and evacuation traffic flow problems with time dependent demand uncertainty. This paper studies a Cell Transmission Model (CTM) based system optimum dynamic traffic assignment model. We adopt a min–max criterion and apply an extension of the RO method adjusted to dynamic optimization problems, an affinely adjustable robust counterpart (AARC) approach. Simulation experiments show that the AARC solution provides excellent results when compared to deterministic solution and sampling based stochastic programming solution. General insights of RO and transportation that may have wider applicability in humanitarian relief supply chains are provided.

1. Introduction

Over the past three decades, the number of reported disasters have risen threefold. Roughly, 5 billion people have been affected by disasters with an estimated damages of about 1.28 trillion dollars (Guha-Sapir et al., 2004). Although most of these disasters could not have been avoided, significant improvements in death counts and reported property losses could have been made by efficient distribution of *supplies*. The supplies here could mean personnel, medicine and food which are critical in emergency situations. The supply chains involved in providing emergency services in the wake of a disaster are referred to as *humanitarian relief supply chains*. Humanitarian relief supply chains are formed within short time period after a disaster with the government and the NGO's being the major drivers of the supply chain. Clearly, emergency logistics is an important component of humanitarian relief supply chains.

Most literature in emergency logistics focuses on generating transportation plans for rapid dissemination of medical supplies inbound to the disaster hit region (Sheu, 2007; Ozdamar et al., 2004; Lodree and Taskin, 2008). There is, however, another aspect of emergency logistics which is often ignored – outbound logistics. The outbound logistics considers a situation where people and emergency supplies (e.g. medical facilities and services for special need evacuees) need to be sent from a particular location affected by disaster within a given time horizon.

In the outbound emergency logistics, the demand of traffic flows is usually highly uncertain and depends on a number of factors including the nature of disaster (natural/man-made) and time of impact. This uncertainty in the demand causes disruptions in emergency logistics and hence disruptions in humanitarian relief supply chains leading to severe sub-optimality or even infeasibility which may ultimately lead to loss of life and property. In order to mitigate the risk of uncertain demand,

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we study the problem of generating evacuation transportation plans which are robust to uncertainty in outgoing demand. More specifically, we solve a dynamic (multi-period) emergency response and evacuation traffic assignment problem with uncertain demand at source nodes.

Researchers and practitioners in the field of transportation are concerned with multi-period management problems with an inherent time dependent information uncertainty. Traditional dynamic optimization approaches for dealing with uncertainty (e.g. stochastic and dynamic programming) usually require the probability distribution for the underlying uncertain data to obtain expected objectives. However, in many cases, it may be very difficult to accurately identify the distribution required to solve a problem. Especially, this is more likely true when we are considering an evacuation transportation problem due to the inherent complexity and uncertainty. In addition, the robust solution guaranteeing the feasible evacuation plan is important since infeasible solutions may cause the potential loss of life and property in extreme events.

We explore the potential of robust optimization (RO) as a general computational approach to manage uncertainty, feasibility, and tractability for complex transportation problems. RO approach has been originally developed to deal with static problems formulated as linear programming (LP) or conic-quadratic problems (CQP), using crude uncertainty with hard constraints. It means that uncertainty is assumed to reside in an appropriate set and RO guarantees the feasibility of the solution within the prescribed uncertainty set by adopting a min–max approach. The RO technique has been successfully applied in some complex and large scale engineering design and optimization problems similar as robust control in control theory (Ben-Tal and Nemirovski, 1999, 2002).

The original RO approach considers static problems. The underlying assumption of RO is ‘‘here and now" decisions, and all decision variables need to be determined before any uncertain data are realized. This is not typical in many transportation management problems that have the multi-period nature. In multi-period transportation problems such as dynamic traffic assignment, ‘‘wait and see" decisions are made, which means some decision variables are ‘‘adjustable" and affected by part of the realized data. Recognizing the need to account for such dynamics, Ben-Tal et al. (2004) have extended the RO approach and developed an affinely adjustable robust counterpart (AARC) approach to consider ‘‘wait and see" decisions.

To demonstrate the use of AARC to emergency transportation management settings, in this paper we consider a system optimum dynamic traffic assignment (SO-DTA) problem. The main contributions of this paper are summarized as follows:

- This paper develops a robust optimization framework for system optimum dynamic traffic assignment problems. The framework incorporates a linear programming (LP) formulation based on the Cell Transmission Model (CTM) (Daganzo, 1993, 1995; Ziliaskopoulos, 2000) and the AARC approach by considering dynamical adjustments to realizations of uncertainty with appropriate uncertainty sets. The framework is converted to LP and hence computationally tractable.
- This paper applies the proposed robust optimization framework to an emergency response and logistics planning problem. Numerical examples are provided to illustrate the value of the robust optimization in the context of emergency logistics and demonstrate the computational viability of the developed framework. Simulation experiments show that the AARC solution provides excellent results when compared to with the solutions of deterministic LP and Monte Carlo sampling based stochastic programming.
- This paper obtains some general insights that may have wider applicability for transportation managers: (1) A robust solution may improve both feasibility and performance when infeasibility costs are significant. Intuitively, the usual nominal optimal solution may be not far from the robust solution, but the usual optimal solution can perform much worse in the worst case. (2) An integration of RO and transportation modeling will improve the generation, communication, and potential use of uncertainty data in logistics transportation management. The intuition for this insight is twofold. First, in many applications in transportation, the set-based uncertainty (used by RO) is the most appropriate notion of data uncertainty. Second, computational tractability (resulting from this set-based uncertainty and dynamic traffic flow modeling in LP formulations) lead to efficient solutions for logistics transportation management under uncertainty.

The structure of the paper is as follows. In Section 2, we provide a literature review. Section 3 presents a deterministic LP model for the CTM based SO-DTA problem. In Section 4, AARC is formulated by considering appropriate demand uncertainty sets. We study applications in evacuation transportation and provide experiment results for two emergency logistics planning examples in Section 5. Section 6 concludes and discusses future work.

2. Literature review

The DTA problem describes a traffic system with time-varying flow and has been studied substantially since the seminar work of Merchant and Nemhauser (1978a,b). The main research can be classified into four categories: mathematical programming, optimal control, variational inequality, and simulation-based approach (see Peeta and Ziliaskopoulos (2001), Friesz and Bernstein (2000) for a review).

Daganzo (1993), Daganzo (1995) proposed the CTM model, consisting of a set of linear difference equations, to develop a theoretical framework to simulate network traffic. It was assumed that the best route from origin to destination are already known to the travellers. Ziliaskopoulos (2000) relaxed this assumption by formulating a single destination SO-DTA problem as a linear program with the decision variables being the route choices. Recently, the deterministic CTM based DTA model has been applied to evacuation management (e.g., Tuydes (2005), Chiu et al. (2007), Xie et al. (2010)). For example, Chiu et al.