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A tractable two-stage robust winner determination model for truckload service procurement via combinatorial auctions

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ABSTRACT

A combinatorial auction is one of the adopted mechanisms for truckload (TL) service procurement. In such an auction, the shipper faces a well-known winner determination problem (WDP): the shipper, as the auctioneer, is given bids submitted by a group of carriers. In most literature, WDP is modeled as a deterministic mixed-integer program (MIP) and is solved by standard MIP algorithms. However, in practice, the exact shipping demand is unavailable until after the auction. This shipment volume uncertainty has a significant impact on the solution to WDP. Therefore, a deterministic winner determination model with an estimate of shipment volume may not provide solutions that attain low procurement costs. This paper proposes a new tractable two-stage robust optimization (RO) approach to solve WDP for TL service procurement under shipment volume uncertainty. Assuming that only historical data is available, we propose a data-driven approach based on the central limit theorem (CLT) to construct polyhedral uncertainty sets. In particular, we consider two random cases: independent shipment volume and correlated shipment volume. A two-stage RO model with integer first-stage decision variables and continuous recourse variables is then formulated. We develop a reformulation solution method and use numerical tests to demonstrate that it is much more computationally efficient than the widely adopted Benders' type constraint generation algorithm. We demonstrate by numerical tests that real-world sized instances of TL service procurement problems can be solved by our proposed robust method. Moreover, we compare our robust approach with benchmark and show that it is more tractable and robust to uncertainty.

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1. Introduction

Truckload (TL) transportation is the movement of homogenous freight for a single shipper between a fixed origin and a fixed destination. It is a service provided by TL carriers. The shipper, who is the owner of the freight, can be an agent at any stage of a supply chain (e.g., suppliers, manufacturers, distributors, or retailers). TL transportation is a necessary component of a shipper's logistics system and the associated expenditure accounts for a significant portion of the shipper's overall cost. In many corporations, transportation expenditure accounts for about 30% of the overall cost of goods sold (Chen et al., 2009; Ballou, 1992). From a market perspective, truck transportation accounts for 29% of for-hire transportation services

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expenditure which is about 363.7 billion U.S. dollars in 2007 (RITA, 2009). TL accounts for over half of total trucking expenditure (Sheffi, 2004). Reducing TL service procurement cost can greatly benefit large shippers.

By late 1990s, most shippers were buying transportation service by a request-for-proposal (RFP) process via an auction (Sheffi, 2004). The process documented by Foster and Strasser (1990) is the following: the shipper first estimates the shipping demand on each origin–destination (OD) pair in the coming year. Then it transforms this information into a list of lanes[1] and passes it to every carrier that is invited to the auction. Each carrier quote prices on lanes, and the shipper finally evaluate the bids and selects the winners of each lane. Even nowadays in China's fast-growing logistics market, many fast-moving consumer goods and bulk stock manufacturers still procure transportation services through such a RFP process.[2] However, this standard process inherently neglects lane interdependencies which usually lead to each carrier quoting a higher price on each lane, it has been gradually replaced by combinatorial auction which allows the carriers bidding on packages of lanes[3] (Sheffi, 2004).

Determining the winners of a combinatorial auction so that the total procurement cost to the shipper is minimized is nontrivial. Optimization-based methods have been proposed to tackle the problem (see Caplice and Sheffi (2003) for an example). Since exact volume of shipments in the coming year is not available at the time that the combinatorial auction is conducted for TL service procurement, usually the shipper forecasts the volume of shipments on each lane and conducts the auction with that forecast. However, by this method, when the shipper determines the winners, they do not take into account the costs due to the errors in the predicted shipment volume. For instance, due to limited carrier capacities, if the realized shipment volume is larger than forecasted, it is possible that additional TL service is required from third-party carriers who did not participate in the auction. Thus, extra costs which are not accounted for in the deterministic WDP will be incurred. Therefore, robust winner determination methods are needed that can characterize and mitigate the impact of shipment volume uncertainty on TL service procurement.

Recently, a new bidding structure and a corresponding two-stage stochastic winner determination model for TL service procurement was proposed by Ma et al. (2010). Assuming that the distribution of uncertain shipment volume is exactly known to the shipper, Ma et al. (2010) is a remarkable first attempt to explicitly model shipment volume uncertainty and resolve the corresponding stochastic WDP. However, in many cases the exact distribution of uncertainty may not be available. In fact, often decision maker cannot fit the historical data into any common probability distribution but derive some statistical estimates such as mean and variance. So a method that requires no more than this partial distributional information of uncertainty will be more practical. What is more, as reported in Zhang et al. (2014), sampling-based stochastic WDP can become computationally inefficient when the problem scale is large. So it is desirable to use a numerically tractable method to solve WDP under uncertainty.

Robust optimization (RO) derives optimal solutions in worst-case scenario under uncertainty (Soyster, 1973; El Ghaoui et al., 1997, 2003; Ben-Tal and Nemirovski, 1998, 1999, 2000; Bertsimas and Sim, 2003, 2004). It serves as an alternative to the classical stochastic programming methods that handles mathematical programs under uncertainty. Recently, Bandi and Bertsimas (2012) propose to apply RO to several stochastic systems including queuing networks, auction design, and option pricing. The authors demonstrate their approach is numerically tractable, while the classical approach to these application areas that relies on probability theory-based analysis is often intractable. Inspired by this idea, in order to retain tractability while handling uncertainty, in this paper, utilizing the first and second moments of uncertainty which are always estimable from historical data, we propose a tractable two-stage robust winner determination model.

The main contributions of this paper are summarized as follows:

- This paper refines the bidding structure proposed by Ma et al. (2010) to better characterize the effects on the solution to WDP brought by shipment volume uncertainty. In particular, shortage in carriers' required shipment volume is allowed but will be penalized. Moreover, the model allows multiple carriers to win the same single lane which provides a shipper a higher degree of feasibility to select the winners.
- This paper proposes a data-driven approach to develop a two-stage robust winner determination model. Specifically, unlike most two-stage RO studies, we apply a central limit theorem (CLT) based approach to construct uncertainty sets. By this approach, only mean and variance which are estimable from historical data are needed and we can handle either independent or correlated random shipping demand. We develop a reformulation solution method that is much more efficient than the constraint generation algorithm which is widely adopted in two-stage RO literature.
- This paper applies the proposed method to real-world sized instances of TL service procurement. Numerical examples are provided to demonstrate the value of the proposed two-stage robust winner determination model. Specifically, we use numerical experiments to show that the proposed robust WDP is even more numerically tractable than the deterministic WDP. Moreover, by simulation, we show the RO solution is more robust to shipment volume uncertainty and can result in much lower procurement cost than the benchmark especially when the variance of uncertainty is large.
- The two-stage robust winner determination model proposed in this paper has more potential impacts than the benchmark on TL procurement in practice. The intuition for this insight is threefold. First, in many application scenarios, mean and variance are the only solid statistics available from historical data. The proposed CLT based approach just requires

[1] We use the term "lane" to refer to an "O–D-commodity-period specific flow" as first described by Jara-Diaz (1988).

[2] This is concluded from the first author's experience in interacting with both shippers and carriers in China's logistics market.

[3] In a package bid, the carrier quotes one price on multiple lanes. Usually the lanes in a package will help a carrier form circle trips which can increase backhaul efficiency and cut the operating cost.

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