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A two-stage robust approach for the reliable logistics network design problem

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ABSTRACT

This paper examines a three-echelon logistics network in which all supply and transshipment nodes are subject to disruption. We use uncertainty sets to describe the possible scenarios without depending on probabilistic information. We adopt a two-stage robust optimization approach where location decisions are made before and recourse decisions are made after the disruptions are known. We construct three two-stage robust models, which are solved exactly by a column-and-constraint-generation algorithm. Numerical tests demonstrate that the proposed algorithm outperforms the Benders decomposition method in both solution quality and computational time, and that the system's reliability can be improved with only a slight increase in the normal cost.

1. Introduction

The logistics network design problem (LNDP) is key to achieving efficient operations among suppliers, manufacturers, and customers (Min and Zhou, 2002). Compared to the classical facility location problem, it considers multiple echelons and decides the number of suppliers and warehouses, their locations and capacities, and the product flow throughout the network (Pishvaee et al., 2010). The LNDP decisions are strategic: once facilities are built, they are expected to run long term, because it is normally expensive to open and close facilities. Tactical (e.g., supplier and distribution channel selections) and operational (e.g., vehicle scheduling) decisions are based on strategic decisions. Therefore, the value of logistics network design is acknowledged in both academia and industry (Cordeau et al., 2006; Peng et al., 2011; Melo et al., 2009).

One importance aspect in LNDP is to deal with uncertainty, like uncertain set-up costs of facilities, uncertain transportation costs and customer demands (Alumur et al., 2012; Mišković et al., 2017). Facility disruption is another type of uncertainty. Natural disasters (earthquakes, hurricanes, etc.) or industrial accidents (traffic or power interruption, etc.) can cause carefully constructed facilities to be partially or completely destroyed, which may result in higher recourse/mitigation costs. Even minor disruptions can have a significant impact on sales growth and stock returns, and it normally takes a long time for companies to recover (Snyder et al., 2016). Therefore, many authors, including Snyder and Daskin (2005), Cui et al. (2010), An et al. (2014), and Zhang et al. (2015), suggest considering disruptions and the corresponding recourse operations in the system design phase.

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Several probability-based models have been proposed (Snyder and Daskin, 2005, 2006; Cui et al., 2010; Chen et al., 2011; Shen et al., 2011; Teimoury et al., 2013; Qin et al., 2013; Xie et al., 2015). However, in many situations, it is impossible to obtain or predict precise probability information; there may be insufficient historical data or no accurate forecasting method (An et al., 2014; Snyder et al., 2016). For instance, it is difficult to predict earthquakes. Robust optimization (RO) has been proposed to deal with data uncertainty; it does not require probability information because uncertainty sets are employed to capture randomness. It derives solutions that are robust to any disruptions within the set. The static RO method makes decisions here and now, which could be overly conservative and costly. However, the two-stage RO approach is able to generate less conservative solutions, because it makes recourse decisions based on observed information. Therefore, it has been used to model unit commitment problems in the power industry (An and Zeng, 2015), location–transportation problems (Zeng and Zhao, 2013), and *p*-median facility location problems (An et al., 2011).

In this paper, we use a two-stage RO scheme for a network design problem that considers disruption. In the first stage, we make location decisions based on any realization in the uncertainty set; and in the second stage we make recourse decisions based on the first-stage location decisions and the revealed uncertainty. Our study makes the following contributions:

(i) To the best of our knowledge, this paper is the first to solve the reliable LNDP using a two-stage RO approach, which is able to produce less conservative solutions.
(ii) The RO model can be extended to include multiple uncertainty sets and impose upper bounds on the worst-case performance of these sets. It can also be extended to partial disruptions.
(iii) We present an exact algorithm that outperforms the Benders decomposition (BD) method. We present management insights based on the numerical results.

The rest of this paper is organized as follows. Section 2 reviews the literature. Section 3 describes our problem and presents three two-stage RO models. Section 4 introduces an exact algorithm for the models, and Section 5 presents the numerical results. Section 6 concludes the paper and suggests future research directions.

2. Literature review

Supply chain disruption is not a new concept; it has existed as long as the supply chain itself. However, in recent years it has received increasing attention. Snyder et al. (2016) give four reasons for the explosion of interest: (1) high-profile events, such as the 9/11 terrorist attack in the United States and the Japanese earthquake, have brought disruption to the forefront of public attention; (2) the "just in time" concept leaves little room for adjustment, and this significantly exacerbates the impact of disruption; (3) with the development of the global supply chain, suppliers are more integrated and some are located in economically or politically unstable regions; (4) as with any other maturing research area, scholars study this topic because of its high profile.

Drezner (1987) was the first to present mathematical models for location problems with unreliable facilities. In the unreliable *p*-median problem (PMP) a facility has a given probability of becoming inactive; in the (*p, q*)-center problem *p* facilities need to be built and at most *q* of them will fail simultaneously. Snyder and Daskin (2005) study the reliable PMP and the reliable uncapacitated fixed-charge location problem (UFLP), assuming that each facility that can fail has the same failure probability. Cui et al. (2010) investigate the reliable UFLP and assume that each facility has a site-dependent failure probability. Li and Ouyang (2010) further suppose that the facilities are subject to spatially correlated disruptions. Lim et al. (2010) consider a facility location problem with two types of facilities: unreliable facilities may fail with a probability in the failure state; and reliable facilities will not fail but have higher fixed costs. Rayat et al. (2017) solve a multi-product and multi-period reliable location-inventory-routing problem, where an unreliable distribution center (DC) has a possibility to be disrupted in each period. Farahani et al. (2017) consider a multi-product location-inventory problem. They assume that product *k* may be out of stock when facility *j* is partially disrupted, and customers can purchase substitute products from facility *j* or try another facility to obtain the same product. For more details on the reliable facility location problem see Snyder et al. (2016) and Sawik et al. (2018).

Although supply chain disruption has received extensive attention, research into disruption in the context of network design is scarce (Snyder et al., 2016). The reliable LNDP extends the reliable facility location problem by considering multiple echelons and allowing transshipment nodes in addition to supplier and demand nodes. Both the supplier and transshipment nodes can be destroyed. It also considers facility capacities.

Snyder et al. (2006) propose several scenario-based models (each scenario has an occurrence probability) for designing supply chains that are resilient to disruption. They first present a reliable network design model for a network that will be built from scratch. For existing networks, they provide fortification models and indicate that the reliability of the existing facilities can be enhanced by investing in protection and security measures. Peng et al. (2011) study a reliable LNDP with a $p-$robustness criterion, the objective of which is to minimize the nominal cost. They propose a scenario-based mixed-integer programming (MIP) model and develop a hybrid genetic algorithm. In their numerical tests they randomly generate several scenarios, where each facility has a 10% probability of becoming disabled. Azad et al. (2013) consider a capacitated supply chain network design (SCND) model in which both the facilities and the transportation network have a given probability of disruption. They assume that the facilities are partially destroyed when disruptions occur and that the customers of a disrupted DC are not assigned to other DCs; instead, the capacity lost at the disrupted DC is replenished from non-disrupted DCs. They formulate a linear MIP model and propose a modified BD method. Shishebori et al. (2014) study a reliable facility