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Resilient facility location against the risk of disruptions

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A B S T R A C T

In this paper, we consider an uncapacitated facility location problem (RUFL) with random facility disruptions. We develop risk-averse optimization formulations to compute resilient location and customer assignment solutions for two cases (i.e., under either independent or correlated disruptions), where the risks are expressed through a family of risk measures including conditional value-at-risk (CVaR) and absolute-semideviation (ASD). The risk-averse RUFL with independent facility disruptions is to control the risks at each individual customer and modeled as a mixed-integer nonlinear programming, which is challenging to be solved. In response, we develop a branch-and-cut algorithm combined with augmented Lagrangian decomposition for globally optimizing the problem. As for the risk-averse RUFL with correlated facility disruptions, we propose a scenario-based model to minimize the total fixed costs and risks across the entire customer set. The resulting formulation is a pure MILP and a Lagrangian decomposition scheme is proposed for computational aspects in large-scale cases. Our numerical results show that the risk-averse models outperform the classic risk-neutral models in improving the reliability. Experiments demonstrate that our proposed algorithms perform well. To conclude, we extract managerial insights that suggest important guidelines for controlling risk in the face of disruption.

1. Introduction

Proper facility location is the key to attracting customers and generating profit. Moreover, constructing facilities is usually very costly, and the locations cannot be easily modified once chosen. Thus, facility location is regarded as a crucial issue in supply chain design. In practice, facilities face the risk of disruption from both man-made and natural disasters. When a facility fails, its customers may either seek service from another operational facility or give up service. In either case, the supply chain faces potentially major losses. This reality forces designers to create resilient supply chains with built in disruption mitigation.

In the reliable facility location literature, a stochastic optimization problem is solved where the objective is to minimize the total expected cost, including the one-time setup cost, the expected day-to-day transportation cost, and any penalty costs (Cui et al., 2010; Snyder and Daskin, 2005; Li and Ouyang, 2010; Mak and Shen, 2012; Berman et al., 2017; Lim et al., 2013; Lu et al., 2015; Li et al., 2013a). In these models, it is assumed that the decision maker is risk-neutral under the facility disruptions. However, most supply chain managers are depicted as risk-averse instead of as risk-neutral (Bromiley and Curley, 1992). Several studies of risk preferences in related fields also attest to risk-awareness in optimization (Berman et al., 2017; Schmitt et al., 2015; Mak and Shen, 2012). Furthermore, it has been argued that a risk-averse approach for

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decision-making problems under uncertainty can provide more robust solutions compared to the risk-neutral approach (Noyan, 2012). Despite this importance, the literature has a few discussion on risk preferences in facility location problems.

Risk measure is a well-established tool for quantifying the risk preference of a decision-maker. Our paper aims to incorporate risk measures in the context of reliable uncapacitated facility location (RUFL). We develop models based on downside risk measures (i.e. conditional-value-at-risk (CVaR)) and absolute - semideviation (ASD)) to incorporate the risk preference. This paper makes three main contributions:

(i) First, we propose an attractive class of stochastic optimization problems to incorporate risk preferences to control the risks at each individual customer in reliable facility location under random independent facility disruptions. We aim to minimize the total fixed costs and control risks at each individual customer. The resulting RUFL models based on CVaR and ASD in this paper are formulated as 0–1 mixed-integer nonlinear programming (MINLP) problems, i.e., non-convex optimization. Different from the existing models in which the customer assignment probabilities are constant parameters (Soleimani et al., 2014; Berman et al., 2017; Azad et al., 2014), we relax customer assignment probabilities as decision variables. Compared to existing models, this setting actually makes our model more general in the face of facility disruptions. We prove that our risk-averse model can transformed into the classic risk-neutral models $\left(\text{if } \mathrm{VaR}^{\mathrm{i}}_{\alpha}(Y,P)=0\right)$ and max-risk models $\left(\text{if } \mathrm{VaR}^{\mathrm{i}}_{\alpha}(Y,P)=\max_{j\in J} C_{ij}\right)$ under certain conditions, more details in Section 4.2. In addition, increasing risk awareness of the decision maker can result in selecting more reliable facilities. Thus, the risk-averse models are proved to be more reliable than classic expected models and less conservative than maximum risk models. To the best of our knowledge, this is the first risk-aware non-convex model of reliable uncapacited facility location problem.

(ii) Second, we develop a branch-and-cut algorithm combined with augmented Lagrangian decomposition for globally optimizing the proposed MINLP. The proposed solution algorithm is to generate tight relaxations via cuts derived from augmented Lagrangian decomposition for each subproblem and find lower bounds. The algorithm avoids the requirements of some traditional non-convex solution methods, e.g., the continuous and differentiable constraints for the pure augmented Lagrangian approach, the strong relaxations for RLT, and the large multipliers for the penalty method. Numerical experiments confirm that our algorithm outperforms CPLEX.

(iii) Third, we extend the risk-averse models of RUFL to consider correlated facility disruptions. We propose a scenario-based model to minimize the total costs and risks across the entire customer set, which differs from the previous risk-averse RUFL model under independent facility disruptions. We show that the problem can be modeled as a pure MILP, and propose the corresponding algorithm based on Lagrangian relaxation and decomposition to solve large-scale problems. Compared to risk-neutral model, we prove that the risk-averse model is more reliable than classic risk-neutral models and less conservative than the worst-case models.

The paper is organized as follows. In Section 2, we present a literature review of facility location problems and risk-aware decision-making. In Section 3, we review preliminary material on risk measures. Section 4 proposes our main optimization problem which accounts for risk preferences in facility location problems. Section 5 develops our solution algorithm based on branch-and-cut combined with augmented Lagrangian decomposition. In Section 6, we discuss the risk-averse models of RUFL with correlated facility disruptions. We present computational results demonstrating the efficiency and effectiveness of the developed algorithm and comparisons with traditional approaches in Section 7. The paper concludes in Section 8 with a discussion of the future research directions.

2. Literature review

Reliable facility location under facility disruptions is an emerging body of research in the logistics literature. One of the earliest mathematical models is proposed by Drezner (1987), who considers an unreliable p-median and (p, q)-center location problem, where a facility becomes inactive with a given probability. Snyder and Daskin (2005) study the p-median uncapacitated fixed-charge location problem and present an implicit formulation based on level assignments, where each potential location is subject to random disruptions with equal probabilities. In light of the level assignments strategy, An et al. (2015), Berman et al. (2007), Aboolian et al. (2012), Cui et al. (2010), Li and Ouyang (2010), Li et al. (2013b), Lim et al. (2010), Snyder and Daskin (2006) and Xie et al. (2015) formulate their models by assuming correlated probabilistic disruptions or relaxing the assumption of uniform facility failure probabilities.

An et al. (2014) propose a set of two-stage robust optimization models for reliable p-median facility location design to cope with two practical issues, i.e., facility capacities and demand losses due to disruptions. An improved column-and-constraint generation approach is developed to solve the robust formulation. An et al. (2015) present a scenario-based stochastic mixed-integer nonlinear program (MINLP), which integrates several factors such as facility disruption risks, en-route traffic congestion, and in-facility queuing delay into a facility location problem. They propose a Lagrangian relaxation (LR) based approach for computing lower and upper bounds on the optimal solution. Chen et al. (2011) present an integer programming formulation to minimize the sum of fixed costs, expected inventory costs, and expected customer costs under the risk of probabilistic facility disruptions. They also present a Lagrangian relaxation solution for this problem. By assuming independent disruptions, Li and Ouyang (2010) present a continuum approximation model to account for the correlation among adjacent facility disruptions. Following this continuum approximation model, Li et al. (2013b) formulate a