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A sample average approximation approach for supply chain network design with facility disruptions

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ABSTRACT

In this paper, we propose a sample average approximation (SAA) algorithm to solve the supply chain network design problem involving facility disruptions. This problem is formulated as a two-stage stochastic programming model as well as an explicit scenario-based model. We solve the models using SAA with a scenario decomposition algorithm to solve each sample problem. Three alternative subroutines for the scenario decomposition algorithm are proposed in order to accelerate the algorithm. The performances of these alternatives are compared in computational experiments. The results show that high-quality solutions with performance guaranty can be obtained through this proposed approach.

1. Introduction

In this paper, we consider an uncapacitated facility location problem (UFLP) with possible facility disruptions. In the classic UFLP, one needs to select a set of facilities to operate from potential locations and determine customer assignments, and the goal is to minimize the total cost that consists of initial facility setup cost and day-to-day transportation cost (Cornuéjols, Nemhauser, & Wolsey, 1983; Snyder et al., 2016). However, due to uncertainties, endogenous or exogenous to the system, a facility may fail and lose its total capacity. When such a facility failure occurs, the customers may have to be reassigned to other working facilities, which incurs a higher transportation cost (Cui, Ouyang, & Shen, 2010; Snyder & Daskin, 2005, 2007). There are wide applications of facility location problems (FLP), ranging across critical infrastructure sectors such as communications, emergency services, commercial facilities, defense industrial base, and so on (DHS, 2018). In this study, we investigate the UFLP under the context of supply chain network.

Supply chain uncertainty exists by its nature. In practice, there is a wide range of reasons that may lead to facility disruptions. The uncertainty may be caused by the supply chain itself, i.e., major breakdowns of equipment, power outages, industrial accidents; or from natural disasters, such as earthquakes and hurricanes; or from other reasons like political disturbance, terrorist and cyber attacks. Though facility failures rarely happen, when it happens, it often interrupts the normal operations and causes high costs. There are many well documented examples of facility failures, and the significant cost associated. For example, a fire at the Philips microchip factory in Albuquerque, New Mexico in 2000 caused a significant impact on its two customers, Nokia and Ericsson. The estimated short-term revenue losses for Ericsson were at least $400 million, and the long-term impact was even greater (Latour, 2001). Other infamous examples include Hurricane Katrina in 2005 and the Tohoku-Kanto Earthquake and Tsunami in 2001. More recent examples include Hurricane Maria in 2017, when these types of natural disasters happen, they cause not only physical damage to the region but also incremental damage to supply chains.

Consolidation of existing facilities is one option to deal with the disruption risks within supply chains; however, an alternative and robust approach is to take the failure risk into consideration at the supply chain design phase (O'Hanley, Scaparra, & García, 2013). By considering these uncertainties during supply chain design phase, the decision maker is able to assess and potentially reduce the risk of high costs that caused by uncertainty. When considering the facility failure possibility, there are commonly two perspectives to view the problem, which focus on the average performance and the worst-case performance, respectively. In this paper, we consider the former, and the object is to minimize the expected system total cost.

The reliable location model considering supply disruptions was first introduced by Snyder and Daskin (2005). They are motivated by a facility location problem of 49 cities in United States. They notice that facility failures at one key city will result in a significant increase of transportation cost. For example, with the solution of UFLP problem, if the facility in Sacramento, California becomes unavailable, the west-coast customers must be served from facilities in Springfield, Illinois

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and Austin, Texas, resulting in an increase of transportation cost of 112%. They propose a scenario-based model for the reliable location model, which has an exponential number of scenarios. Besides the scenario-based model, an implicit model in which the random disruptions are modeled implicitly is proposed with the assumption that all sites have identical failure probability. Cui et al. (2010) relax this assumption and proposed a formulation that allows site-dependent failure rate. However, due to the large size of the model, they are only able to solve the proposed model with a specially designed algorithm by restricting the reassignment level up to 4. A more efficient solution method is proposed by Aboolian, Cui, and Shen (2012), and the algorithm's performance is not significantly affected the reassignment level. Unlike aforementioned works, which assume the facility failures are independent, Li and Ouyang (2010) propose a continuum approximation approach to the problem where the facilities are subject correlated probabilistic disruptions.

In this paper, we apply the sample average approximation (SAA) (Kleywegt, Shapiro, & Homem-de Mello, 2002) method to the reliable facility location problem with disruptions. SAA is a Monte Carlo simulation-based approach to solve discrete stochastic optimization problems. This approach has been successfully applied to solve a wide range of problems that involving uncertainty, some of which include: routing (Verweij, Ahmed, Kleywegt, Nemhauser, & Shapiro, 2003), scheduling (Mancilla & Storer, 2012) and supply chain network design (Santoso, Ahmed, Goetschalckx, & Shapiro, 2005; Schütz, Tomasgard, & Ahmed, 2009). With this framework, we are able to solve problems with higher site-dependent failure probabilities as well as correlated disruptions. Moreover, this framework could be used to solve general supply chain network design problems that consider disruptions, e.g., multi-echelon supply chain network design, capacitated facility location problem, for which implicit models rarely exist. We adopt a recently proposed scenario decomposition algorithm to solve each of these sample problems. Further, to accelerate this algorithm, we propose several alternative strategies and compare the performance in the computational experiments which are based on randomly generated instances.

The remainder of this paper is organized as follows. We review the closely related models in the literature in Section 2. We define the notations and present the mathematical formulations for the supply chain network design problem with facility disruptions in Section 3. In Section 6 we conclude the paper.

2. Literature review

While classic facility location models focus on deterministic problems, stochastic and robust facility location models have been developed to address design uncertainty. For further information, refer to Snyder (2006) for a comprehensive review in this area. The issue of facility disruptions has attracted more attention in recent years. Recently, researchers have focused on assessing or mitigating the disruption risk of supply chains (Christopher & Lee, 2004; Liberatore, Scaparra, & Daskin, 2012; Tang, 2006; Tang & Tomlin, 2008; Tomlin, 2006). This review will be restricted to the topic of supply chain network design with disruptions.

Snyder and Daskin (2005) considered both the p-median problem and the UFLP problem where the facilities are subject to equal failure probability. The explicit formulation is computationally intractable due to the extremely large number of possible disruption scenarios. They then presented an implicit nonlinear integer programming model for the problem, which used the concept of "level assignments" and developed a Lagrangian decomposition to generate an optimal solution for the model. The reliable p-median problem was further studied by Berman, Krass, and Menezes (2007), and the authors formulated an implicit nonlinear integer programming model that allowed for facility failures with heterogeneous probabilities; the model also utilized heuristic and exact approaches to solve the problem.

Cui et al. (2010) extended the work of Snyder and Daskin (2005) by proposing an implicit nonlinear model with a relaxed assumption of equal failure probabilities. The authors further presented an equivalent linear model to a proposed nonlinear model and developed a Lagrangian relaxation algorithm to solve the linear model. They also provided a continuum approximation model for the problem. A similar problem is studied by Shen, Zhan, and Zhang (2011), in which the authors proposed a two-stage stochastic model and a nonlinear integer programming model and then used heuristics to find a near optimal solution. O'Hanley et al. (2013) provided an alternative linearization method for reliable facility location models with site-dependent failure probabilities. This model is highly compact and requires fewer variables and constraints than the model proposed by Cui et al. (2010). Peng, Snyder, Lim, and Liu (2011) presented an integer programming model that minimized total cost when no disruption occurs and used p-robustness criterion to bound the cost in disruption scenarios. They proposed a hybrid meta-heuristic algorithm and showed that it outperforms CPLEX in terms of solution speed, while still delivering adequate quality. Recently, Aboolian et al. (2012) developed algorithms that contains local search heuristics and cutting plane procedures for the problem by Cui et al. (2010). They showed that their method outperformed the Lagrangian relaxation algorithm in both execution time and solution quality.

Recently, several studies have been conducted about integrated supply chain network design problems considering facility disruptions. Chen, Li, and Ouyang (2011) studied a reliable version of integrated supply chain network design problem that was studied by Daskin, Coullard, and Shen (2002) and Shen, Coullard, and Daskin (2003). The problem requires strategic and operational decisions, as well as considering disruption risks in the supply chain design phase. To solve this problem, they also proposed an integer programming model and a Lagrangian based solution method. Qi, Shen, and Snyder (2010) investigated a similar problem, and they showed significant cost savings from considering supply disruptions at the supply chain design phase.

In aforementioned works, it is often assumed that the disruptions are uncorrelated and independent of each other. Studies about reliable facility location problems under correlated facility disruptions are still rare. Li and Ouyang (2010) developed a continuum approximation for a reliable facility location problem where facilities are subject to spatially correlated disruptions that occur with location-dependent probabilities. A similar problem is studied by Lu, Ran, and Shen (2015), in which the authors applied distributionally-robust optimization to minimize the expected cost under the worst-case distribution with pre-specified marginal disruption probabilities. In this paper, we investigate the reliable facility location problem with disruptions. The major contribution of the paper is twofold. First, we model the supply chain network design problem with facility disruptions as a two-stage stochastic programming model with a scenario-based formulation. Second, we develop a general method, sample average approximation, which is able to solve this problem efficiently with statistical bounds, regardless of the disruptions being correlated or not.

3. Problem description and formulations

The supply chain network design problem with facility disruptions (SCND-FD) is described as follows: consider a two-echelon supply chain network consisting of a set of potential facility locations, denoted by J, indexed by j, and a set of customers, denoted by I, indexed by i. Products must be delivered from facilities to customers, and each customer $i \in I$ has a demand rate of h_i. There is an initial facility setup cost f_j to open a facility. The unit shipment cost from facility $j \in J$ to customer $i \in I$ is denoted by d_{ij}. Facilities are unreliable and face unexpected failures with a site-dependent failure rate q_j. We use an "emergency" facility E to meet customer demand and model a system-wide penalty when all other facilities fail. The emergency facility has an initial setup cost of 0, i.e., $f_E = 0$, and the unit shipment cost is equal to