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Investigating risk and robustness measures for supply chain network design under demand uncertainty: A case study of glass supply chain

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ABSTRACT

This paper addresses a multi-stage and multi-period supply chain network design problem in which multiple commodities should be produced through different subsequent levels of manufacturing processes. The problem is formulated as a two-stage stochastic program under stochastic and highly time-variable demands. To deal with the stochastic demands, a Latin Hypercube Sampling method is applied to generate a fan of scenarios and then, a backward scenario reduction technique reduces the number of scenarios. Weighted mean-risk objectives by using different risk measures and minimax objective are examined to obtain risk-averse and robust solutions, respectively. Computational results are presented on a real-life case study to illustrate the applicability of the proposed approaches. To compare these different decision-making situations, a simulation approach is used. Furthermore, by several test problems, the performance of the stochastic model is investigated and the scenario generation method is evaluated in terms of in-sample and out-of-sample stability. Finally, sensitivity analysis on main parameters of the problem is performed to drive some managerial insights.

1. Introduction

Supply chain management (SCM) was introduced by Webber and Oliver in early 1980s as a response to the business competitive environment. Finding the best possible supply chain configuration is a crucial part of planning processes in SCM known as supply chain network design (SCND) (Melo et al., 2009). Due to the stochasticity inherent within some main parameters of SCND problems, such as demands, costs, facilities' capacity, etc., stochastic programming models have been much attracted in this context during the last two decades. A two-stage stochastic programming model for design and planning a multi-stage supply chain network with two facility location layers is presented in this paper.

Traditionally, stochastic SCND problems are risk neutral in which an expectation criterion is taken into account as an objective function. However, strategic decisions that usually consist of the number, locations, and the capacity of supply chain network's facilities can really influence the efficiency of decisions related to tactical and operational planning levels; hence, these decisions have a long lasting impact on the supply chain performance (Fattahi et al., 2015b). Therefore, obtaining a robust supply chain configuration and reducing operational risks are matters of particular importance. In this paper, we examine different mean-risk objectives for the SCND problem to reduce operational risks of the network in terms of cost efficiency. Different risk measures such as variance, deviation from a predetermined target, central deviation, value at risk (VaR), and conditional value at risk (CVaR) have been addressed in stochastic programming models and partly applied in SCM context (see Tang (2006), Heckmann et al. (2015), and Ahmed (2006)). In this study, the effects of various risk measures (semideviation from a target, central semideviation, and CVaR) on the solution of the SCND problem are investigated through a simulation approach. In accordance to Ahmed (2006), the risk measures that are addressed in this paper are suitable for stochastic programs in terms of computation.

Rosenhead et al. (1972) categorized decision-making environments into three groups: certainty, risk, and uncertainty. In decision making under risk, there are uncertain parameters with known probability distributions and under uncertainty; information about probability distributions of the parameters is not known. Most robust optimization approaches are extended for the optimization problems under uncertainty situations. Minimax cost and regret are popular approaches for obtaining a robust configuration for supply chain networks (Snyder, 2006). In this paper, a minimax cost objective is also examined for the problem and a comparison between risk-averse and robust solutions for the

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problem is addressed using a simulation method. To our knowledge, this paper is the first one to examine such an investigation in the area of SCND problems.

In designing supply chain networks to have a flexible network configuration, the combination of a multi-period planning horizon with stochasticity is an important issue when the probabilistic behavior of stochastic parameters changes over time. In many real-life supply chains, the customers' demands for multiple products meaningfully change over the planning horizon, so it is essential to consider multiple periods for the problem. In the related literature, risk-averse stochastic programming models with multiple periods have been addressed by a few papers such as Guillén et al. (2005) and Klibi and Martel (2013).

Another main issue in scenario-based (two- and multi-stage) stochastic programs is that generating scenarios and obtaining their probabilities could be problematic specifically in real-life problems. In the context of stochastic SCND problems, many studies such as Schütz et al. (2009), Santoso et al. (2005), and Bidhandi and Yusuff (2011) applied sample average approximation (SAA) to handle scenarios by repeatedly solving the problem with small sets of scenarios. However, this approach is not extended for risk-averse stochastic programs. To overcome this issue, Latin Hypercube Sampling (LHS) is applied in this paper to generate a fan of scenarios. Then, a backward scenario reduction technique is used to reduce the number of scenarios. We evaluate the scenario generation method in terms of in-sample and out-of-sample stability.

In this paper, a three-level supply chain network, including suppliers, production plants, and warehouses, is defined. We develop a two-stage stochastic program to find locations of production plants, warehouses, and capacity levels of manufacturing processes at production plants in the first stage. Furthermore, the main tactical decisions should be obtained in the second stage. The proposed stochastic optimization problem is under uncertain demands of customer zones. Furthermore, multiple tactical periods are considered for the second stage to capture the time variability of demands. Other real-life aspects of the network include: multi-product production, product flows through the facilities in the same echelon of the network (Intra-layer flows), capacitated product flows through the network, and different available transportation modes between supply chain entities. Finally, the contributions of this paper are summarized as follows:

- A new stochastic SCND problem is formulated using two-stage stochastic programming in which multi-product production should be performed through different subsequent levels of manufacturing processes.
- Using LHS and backward scenario reduction, a set of scenarios and their corresponding probabilities are obtained to cope with demands' stochasticity.
- Weighted mean-risk objectives with different risk measures and minimax cost objective are examined for the problem. Through a simulation approach, the effects of these objectives on the supply chain configuration are investigated.
- A real-life case study related to an Iranian glass supply chain under stochastic and highly time-variable demands is considered to investigate the applicability of the proposed stochastic model.

The remainder of this paper is structured as follows: in Section 2, the existing literature related to this study is reviewed. The supply chain description and the scenario generation procedure are presented in Section 3. In Section 4, two-stage stochastic programming formulations with weighted mean-risk objectives and minimax cost objective are generally presented and then a generic mathematical model is developed for the problem. A real-life case study based on an Iranian glass supply chain is explored in Section 5. Computational results are provided in Section 6. Finally, Section 7 contains conclusions and future research directions.

2. Literature review

In this section, a literature review is presented in accordance with the scope of the paper. SCND is a suitable application for facility location (FL) problems and belongs to discrete location models (Melo et al., 2009). In contrast to stochastic facility location problems with one location layer, fewer researchers have addressed stochastic models for the SCND.

The main characteristics of SCND problems are the number of echelons, the type of echelons, and the echelons in which location decisions are made. In addition, several studies considered the multi-commodity aspect in the network (Fattahi et al., 2015a). Santoso et al. (2005) proposed a two-stage stochastic program for a multi-commodity SCND problem including suppliers, manufacturing centers, finishing facilities, and warehouses. They also proposed a solution algorithm for solving the problem with a realistic scale. In Alonso-Ayuso et al. (2003), a two-stage stochastic programming model for designing a supply chain network including suppliers and plants is presented. In their work, binary decisions related to plant sizing, product allocation among plants, and supplier selection for raw materials are assumed to be first stage decisions, and tactical continuous decisions are considered as second stage decisions. In stochastic SCND problems in which decisions related to strategic and tactical planning levels should be determined simultaneously, it is appropriate to create an optimization model using two-stage stochastic programming. Therefore, this approach has been used by most of the studies in this area (e.g. see Alonso-Ayuso et al. (2003), Santoso et al. (2005), Aghezzaf (2005), Schütz et al. (2009), Bidhandi and Yusuff (2011), Noyan (2012), Georgiadis et al. (2011), Longinidis and Georgiadis (2011), and more). Generally, in these studies, the first stage decisions belong to the strategic planning level, and second stage decisions are tactical planning decisions. Furthermore, multi-stage stochastic programming has been applied in few studies such as Goh et al. (2007), Nickel et al. (2012) and Pimentel et al. (2013). In the area of stochastic FL and SCND problems, scenario-based approaches such as two-stage and multi-stage stochastic programming result in more tractable models (Snyder, 2006). Our focus in this section is to review the research studies related to this area.

A multi-period planning horizon in which stochasticity is assumed for some parameters is also considered as another main aspect in the related literature. Several studies such as Aghezzaf (2005), Alonso-Ayuso et al. (2003), Albareda-Sambola et al. (2013), Nickel et al. (2012), Pimentel et al. (2013), and Cardoso et al. (2013) considered these periods as strategic planning intervals; these problems are usually called dynamic SCND problems. Another group of stochastic multi-period SCND problems considered the periods as tactical/operational planning intervals. In these studies, such as what our case proposes (e.g. see Longinidis and Georgiadis (2011), Georgiadis et al. (2011), and Schütz et al. (2009)), a two-stage stochastic programming model is presented in which the second stage has multiple periods.

Furthermore, several studies (see Listeş (2007), Lee et al. (2010), and De Rosa et al. (2013)) integrated the forward network with the reverse one. The reverse logistics networks are often designed for the purpose of collecting used, refurbished, or defective products from customers and then carrying out some recovery activities. Additionally, uncertainty issues related to the return quantities and other parameters of the reverse network play a significant role in designing them. Moreover, the complexity of integrated forward/reverse logistics networks increases in comparison to forward networks. Generally, the echelons corresponding to the forward direction include