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Multi-objective stochastic multi-site supply chain planning under demand uncertainty considering downside risk

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ABSTRACT

In this paper, a multi-period, multi-product, multi-site, multi-stage supply chain planning problem under demand uncertainty is considered. The problem is formulated as a two-stage stochastic linear programming model. In order to generate a robust supply chain planning solution, the downside risk is incorporated into the objective functions of the stochastic programming model as a risk measure. So, the proposed multi-objective stochastic model aims to simultaneously minimize the expected total cost, to minimize the lost customer demand level and to minimize the downside risk. The proposed solution approach yields to a front of Pareto optimal robust solutions. A fuzzy decision making approach is applied to select the most preferred solution among the Pareto optimal robust solutions. A numerical example from a real textile and apparel industry is addressed in order to illustrate the robustness of the supply chain network planning solutions and the effectiveness of the solution approach.

1. Introduction

In the context of multi-site supply chain management, integrated approaches for production and transportation activities planning need to be developed. Such approaches should coordinate all the production resources of the different plants starting from the procurement and storage of raw materials and ending with the shipping of finished products to the customer. The supply chain planning problem can be classified following the time horizon into three major categories: strategic, tactical, and operational (Fox, Barbuceanu, & Teigen, 2000). The focus of this work is to examine the tactical level of the supply chain planning. The optimization of cost and profit are the most commonly considered objectives in the literature of supply chain planning problem. Besides, the customer demand satisfaction level is another important criterion which reflects the performance of the supply chain (Wang, 2001). In fact, a low customer demand satisfaction level could lead to lost sales, high costs and unsatisfied customers. However, the minimization of the supply chain related costs and the maximization of customer demand satisfaction are contradictory objectives.

A lot of attempts have been made in the literature to model and to optimize multi-site supply chain planning problems. Most of these works rely on deterministic approaches that assume that all parameters of the optimization model are known with certainty. One can refer to Moon, Seo, Yun, and Gen (2006), Ryu and Pistikopoulos (2007), Lin and Chen (2007), Verderame and Floudas (2009), Shah and Ierapetritou (2012), Chen (2012) and Felfel, Ayadi, and Masmoudi (2014). In practice, real production planning problems are characterized by several sources of uncertainty such as market demand, sales price and unit cost. Different approaches have been developed in the literature to cope with uncertainty. According to Sahinidis (2004), they can be classified into four categories: robust optimization approach, fuzzy programming approach, stochastic programming approach and stochastic dynamic programming approach. Among the developed stochastic programming approaches, the two-stage stochastic programming technique (Birge & Louveaux, 1997; Dantzig, 1955) has proved its efficiency in solving real-world planning problems under uncertainty (Awudu & Zhang, 2013; Gupta & Maranas, 2003; Leung, Wu, & Lai, 2005). In this approach, the decision variables are partitioned into two sets. The first-stage decisions correspond to variables that need to be taken "here-and-now" prior to revelation of uncertainty. Subsequently, the second-stage decisions are made in "wait-and-see" mode after the revelation of the random events. Therefore, the objective function is calculated based on the first-stage variables and the expected second-stage recourse variables. Gupta and Maranas (2003) studied a multi-product multi-site supply chain planning problem under demand uncertainty using a two-stage stochastic programming approach. The supply chain decisions are divided into two categories: manufacturing decisions

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and logistics decisions. The manufacturing decisions are taken "here and now" before the realization of uncertainty while the logistics decisions are postponed in a "wait and see" mode. Leung et al. (2005) addressed a multi-site aggregate production planning problem under an uncertain environment based on a two-stage stochastic programming technique. The first-stage decisions include the amount of manufactured product in regular-time and overtime, volume of subcontracted products and number of required workers, hired workers and laid-off workers. Decisions such as inventory level of products and amount of under-fulfillment products are considered as second-stage decisions. Awudu and Zhang (2013) developed a two-stage stochastic programming model for a production planning problem in a biofuel supply chain under uncertainty. Amount of products to be produced and amount of raw materials to be purchased and consumed are considered as the first-stage decisions. Decisions such as backlog, lost sales and sold products quantity are considered as second stage decisions. In stochastic programming approach, the expected economic objective is optimized and the average value of the economic objective for all scenarios is improved. However, the stochastic programming technique does not allow to control the unfavorable outcomes and the decision makers are assumed to be risk-neutral in this approach. Felfel, Ayadi, and Masmoudi (2015a) proposed a novel two-stage stochastic model to deal with a multi-site production and transportation supply chain planning problem under demand uncertainty. The robustness of the supply chain planning solutions was then evaluated by means of risk and statistical measures. The results show that solutions robustness should be improved by considering risk management models.

In practice, the decision maker should define a suitable planning while managing the risk of having unfavorable outcomes. This can be considered by including a risk metric associated with the economic objective distribution in the stochastic model. This approach leads to a multi-objective optimization problem where the economic objective and the risk measure are two objective functions to be optimized. The variance is one of the metrics commonly used in the literature to manage the risk and to quantify the variability of the stochastic solution (Leung, Tsang, Ng, & Wu, 2007; Mirzapour Al-e-hashem, Baboli, Sadjadi, & Aryanezhad, 2011). However, the risk management approach based on the variance measure introduces nonlinearities into the mathematical model. Finding the optimal solution for these non-linear large scaled optimization problems becomes very difficult. Moreover, You, Wassick, and Grossmann (2009) demonstrated that managing the variance is not an effective tool to reduce the risk of having high costs. Indeed, the variance management model can give lower variance values but usually reduces the probability of obtaining lower costs and thus increases the risk of high costs. They demonstrated also that managing the financial risk and downside risk are more effective in reducing the probability of high cost than managing variance and variability. Besides, the downside risk outperforms the probabilistic financial risk because it avoids the use of binary variables which will make the size of the model very large with the increasing of scenarios number.

In multi-objective optimization problems, there is more than one objective function which conflict with each other. Hence, there is no solution that optimizes all the objective functions simultaneously. Instead, we are interested in a front of Pareto optimal solutions which represents the trade-off between the different objectives rather than a single solution. So, the task of the decision maker consists in obtaining the front of Pareto optimal solutions and selecting the most comprised solution according to his preferences. Previous work in supply chain optimization problem focused only on generating the front of Pareto optimal solutions and did not address the choice of the most preferred solution (Azaron, Brown, Tarim, & Modarres, 2008; Ben Yahia, Cheikhrouhou, Ayadi, & Masmoudi, 2013; Fahimnia, Farahani, Marian, & Luong, 2013; Franca, Jones, Richards, & Carlson, 2010; Guillen, Mele, Bagajewicz, Espuna, & Puigjaner, 2005; Guo, Wong, Li, & Ren, 2013; Mirzapour Al-e-hashem et al., 2011). Felfel, Ayadi, and Masmoudi (2015b) addressed a multi-objective multi-site supply network planning problem accounting for the minimization of the total cost and the maximization of the product quality level. A lexicographic minimax method is used in order to find a fair solution from the front of Pareto that satisfies equitably the considered objective functions. The main critic of this work is that the authors did not take into account uncertainty in the supply chain planning process. In addition, the lexicographic minimax method generates a fair solution but does not allow to select a solution from the set of Pareto optimal solutions with respect to specific preferences. Although many works in the literature focused on multi-objective supply chain planning problem, to the best of the authors' knowledge, no one of them has addressed the choice of the best solution from the front of Pareto optimal solutions according to the preferences of the decision maker. The fuzzy based decision making methods are widely applied to choose the most efficient solution according to the specific preference of the decision maker in multi-objective electric power system such as congestion management problem in power system (Esmaili, Ali, & Amjady, 2009; Esmaili, Amjady, & Ali, 2011) and electricity market clearing problem (Aghaei, Amjady, & Shayanfar, 2011; Aghaei, Shayanfar, & Amjady, 2010; Amjady, Aghaei, & Shayanfar, 2009). Ben Yahia, Ayadi, and Masmoudi (2015) proposed a bi-level fuzzy-based negotiation approach to model the collaborative planning between many partners of a decentralized manufacturing supply chain. A bi-objective planning model was developed and solved using a genetic algorithm to generate the front of Pareto solution. The obtained front of Pareto was used for negotiation to make the adequate decision by means of the proposed fuzzy logic approach.

The main objective of this paper is to treat a tactical multi-objective, multi-product, multi-period, multi-stage, multi-site supply chain production and transportation planning problem under demand uncertainty. Solutions should be robust and should satisfy conflicting objectives considering decision makers preferences. The rest of the paper is organized as follows. The problem description is presented in Section 2. Section 3 introduces the mathematical formulation of the considered problem. The proposed solution approach is described in Section 4. Section 5 details the application of the developed approach to a real world case from textile and apparel industry as well as the corresponding computational results. Finally, conclusions and future research directions are drawn in Section 6.

2. Problem statement

2.1. Description of the planning problem

The supply chain considered in this paper consists of many production stages. Each stage may include more than one manufacturing plant forming a multi-site supply network structure as illustrated in Fig. 1. A delivery lead time is considered in the transportation of semi-finished and finished products between plants belonging to successive stages and between the last stage plants and customers respectively. The demand of finished products is a random variable. The considered problem aims simultaneously to minimize the expected total cost, to minimize the lost customer demand level, and to minimize the downside risk of incurring in high cost. Despite the fact that the downside risk has been used in other works, to the best of the authors' knowledge, this is the first time that the total cost, the customer demand satisfaction