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On the time-consistent stochastic dominance risk averse measure for tactical supply chain planning under uncertainty[☆]

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ABSTRACT

In this work a modeling framework and a solution approach have been presented for a multi-period stochastic mixed 0–1 problem arising in tactical supply chain planning (TSCP). A multistage scenario tree based scheme is used to represent the parameters' uncertainty and develop the related Deterministic Equivalent Model. A cost risk reduction is performed by using a new time-consistent risk averse measure. Given the dimensions of this problem in real-life applications, a decomposition approach is proposed. It is based on stochastic dynamic programming (SDP). The computational experience is twofold, a comparison is performed between the plain use of a current state-of-the-art mixed integer optimization solver and the proposed SDP decomposition approach considering the risk neutral version of the model as the subject for the benchmarking. The add-value of the new risk averse strategy is confirmed by the computational results that are obtained using SDP for both versions of the TSCP model, namely, risk neutral and risk averse.

1. Introduction

1.1. The problem to be addressed, its importance and difficulty to solve

The deterministic version of the tactical supply chain planning problem (TSCP) that is discussed in this work is based on the real-life case in the assembly sector. It has a broad applicability, specifically, in sectors such as car, computer and domestic appliances manufacturing, among others. It is the case in which a company with multiple raw material suppliers, plants, products, tiers of production in the bill of material (BoM) and markets needs to satisfy a product demand vector over a given time horizon. The goal is to determine a raw material supplying plan and a master production, inventory and distribution planning that best makes use of the available resources and their capacity extension acquisitions in the whole supply chain for each period of a given time horizon. The resources' best use consists of minimizing the raw material supplying commitment cost, the production and inventory costs in the plants, and the product backlog and demand lost penalization along the time horizon. The raw material supplying commitment cost is frequently modeled by a piecewise linear, concave and nondecreasing function of the total volume to commit for the whole time horizon. Typical types of constraints (some of them related to either-or decisions) are as follows: Balance equations of end-products and components, conditional lower and upper bounds for raw material supplying and product release, resource consumption bounds and capacity extension acquisitions, and balance equations of lost demand and backlogging, among others. There are different types of resources at different levels for groups of consecutive periods (so-called stages) along the time horizon. The cost of the resources' capacity extension acquisition is expressed as a piecewise discrete and nondecreasing function. Another important feature of the problem is that that no warehouses are encouraged for intermediate components and products stocking, although some stocking is allowed in the plants. Even the burden of raw material stocking is frequently transferred to the suppliers.

There are many contributions on TSCP for several variants to the case presented above, see the seminal works Cohen and Lee (1989), Escudero (1994) and Shapiro (1993), among others. However, given the volatility in the markets and the dynamic nature of the planning problem, some parameters, besides being not known

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with certainty when decisions are to be made, have high variability in their realizations. Those parameters are the coefficients in the function to minimize (e.g., production cost), the right-hand-side vector (rhs) of some of the constraints (e.g., product demand and resource availability) and the constraint matrix (e.g., product demand lost fraction). Usually, those uncertain parameters are represented by their expected value (EV) and, thus, the parameters' variability is not considered in the model. Hence, the very popular EV strategy is frequently inadequate for problem solving. This work deals with stochastic tactical supply chain planning (STSCP), where the available information about the parameters' uncertainty is represented in the form of a finite set of scenarios. They are considered in the constraints of the model and the expected cost to be minimized. The problem's formulation is so-called deterministic equivalent model (DEM), see in e.g., Birge and Louveaux (2011) the main concepts on stochastic optimization. An important uncertain parameter is the lost demand fraction for the products in each period of the time horizon. Given the high competitive character of the markets, the demand volatility and the potential unavailability of required resources, by no means the non-served demand in a period can be considered with certainty a backlog for the next one. So, the lost demand fraction is uncertain. On the other hand, the time latency in the availability of raw material and subassemblies for production and end-product availability in the markers should be taken into account, due to its strong implication on the related multistage scenario tree.

1.2. Current topics in stochastic optimization

In the presence of uncertain parameters, different approaches for solving nonlinear separable mixed 0–1 problems can be found in the literature in the two-stage and multistage settings. A recent review of decomposition algorithms is presented in Aldasoro et al. (2017), most of the algorithms are intended for problem solving with moderate model dimensions. For bigger instances, some types of scenario cluster decomposition approaches can be used, such as Branch-and-Fix Coordination (Aldasoro et al., 2017; Alonso-Ayuso et al., 2003), two-stage Lagrangean decomposition (Carœand Schultz, 1999), Progressive Hedging algorithm (Gade et al., 2016) and multistage cluster Lagrangean decomposition (Escudero et al., 2016b), among others. For instances with very large dimensions, such as real-life STSCP instances, matheuristic approaches should be used, as the algorithms that belong to the stochastic nested decomposition methodology, see Aldasoro et al. (2015), Cristobal et al. (2009), Escudero et al. (2015) and Zou et al. (2016). Those stochastic optimization approaches deal with the minimization of the objective function expected value alone, so-called risk neutral (RN) strategies. However, the variability of the STSCP cost over the scenarios is not completely taken into account and, then, inducing a negative cost impact of the RN solutions on low-probability high-cost scenarios.

Some approaches that present risk reduction measures are as follows: scenario immunization, see Dembo (1991) and its treatment in Escudero (1995), semi-deviations (Ahmed, 2006; Ogryczak and Ruszczyński, 1999), min-risk (i.e, excess probabilities) (Ahmed, 2006; Schultz and Tiedemann, 2003), value-and-risk (Gaivoronski and Plug, 2005), conditional value-at-risk (CVaR) (Ahmed, 2006; Pflug and Pichler, 2015b; Rockafellar and Uryasev, 2000; Schultz and Tiedemann, 2006) and stochastic dominance (SD) strategies (Escudero et al., 2016a; Gollmer et al., 2011; 2008). For computational comparison of the time inconsistent versions of those measures, see Alonso-Ayuso et al. (2014).

Recent state-of-the-art surveys on risk management, specifically dealing with supply chains, can be found in Esmaeilikia (2013), Esmaeilikia et al. (2016a); 2016b), Fahimnia et al. (2015), Heckmann et al. (2015) and Ho et al. (2015). However, there are only a few recent STSCP works dealing with risk averse measures, mainly CVaR in Alem and Morabito (2013) and Nickel et al. (2012), and mean-risk and minmax for robust solutions in Govindan and Fattahi (2017) presenting real-life cases for validating the proposed approaches, among others.

In addition, most of the approaches presented above are targeting stochastic two-stage problems and specific decomposition algorithms are developed. In a stochastic multi-period two-stage problem, a node in the scenario tree has only one immediate successor and, then, its parameters can only influence on the parameters of the same scenario. So, the non-anticipativity (NA) principle is not satisfied for the variables in any node but the first one.

However, in a multistage setting the realizations in any node in the scenario tree (besides the first one) may have an influence on the parameters of its successor nodes in different scenarios. So, the nodes that belong to any stage (but the first one) have a conditional probability based on their ancestor common node (i.e., it is a Markovian process). Hence, the NA principle should be satisfied for the decision variables of the nodes in the tree with a one-to-one correspondence with the group of scenarios that have identical realizations up to the node-related period.

Additionally, a SD risk averse measure is very appropriate for the STSCP cost risk reduction, since it controls the expected cost excess over a set of modeler-driven increasingly cost thresholds in the scenarios. That control is materialized in a policy for which the higher the cost threshold is, the smaller the modeler-driven upper bounds should be for the expected cost excess over the threshold and the failure probability to satisfy it.

1.3. Main contributions of this work in STSCP problem solving

The main contributions of our work are aimed to reducing some gaps in the literature on STSCP problem solving that have been identified above. They are as follows:

1. Presenting a realistic multi-period STSCP problem with a multi-tier BoM for a multi-product, multi-supplier and multi-market setting, a piecewise linear objective function and uncertainty in dynamic product demand, demand lost fraction, production cost and available resource base capacity.
2. Modeling the STSCP via scenario analysis by using a multi-period mixed 0–1 full recourse Deterministic Equivalent Model (DEM) with S2 sets to represent the piecewise linear terms in the objective function. Because the supplying ordering time lag and transportation time between vendors and plants, origin and destination plants, and end-product plants and markets, the ordering and delivering could belong to different time periods. As a consequence, different modeling objects are required, given the variety of scenarios that may occur in the time interval between the ordering and the delivering.
3. Modeling the risk reduction of the cost impact of the STSCP solutions on low-probability high-cost scenarios (i.e., the black swans). For the reasons that will be fully formalized in Section 4, the dynamic SD risk averse measure takes benefit from a new version so-called expected conditional stochastic dominance (ECSD), that is introduced in this work. It is a time-consistent risk averse measure consisting of a mixture of first- and second-order SD functionals related to a set of modeler-driven profiles in the nodes of a given subset of periods. Each profile is included by a cost threshold, a bound on the expected cost excess over the threshold in the scenario group with a one-to-one correspondence with the nodes of the selected periods, and a bound on the probability of any of those scenarios to fail on satisfying the cost threshold. The rationale behind it is that the solution of any node and its successor node set in the scenario tree should not consider the data, constraints and

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