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A multi-objective robust optimization model for multi-product multi-site aggregate production planning in a supply chain under uncertainty

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ABSTRACT

Manufacturers need to satisfy consumer demands in order to compete in the real world. This requires the efficient operation of a supply chain planning. In this research we consider a supply chain including multiple suppliers, multiple manufacturers and multiple customers, addressing a multi-site, multi-period, multi-product aggregate production planning (APP) problem under uncertainty. First a new robust multi-objective mixed integer nonlinear programming model is proposed to deal with APP considering two conflicting objectives simultaneously, as well as the uncertain nature of the supply chain. Cost parameters of the supply chain and demand fluctuations are subject to uncertainty. Then the problem transformed into a multi-objective linear one. The first objective function aims to minimize total losses of supply chain including production cost, hiring, firing and training cost, raw material and end product inventory holding cost, transportation and shortage cost. The second objective function considers customer satisfaction through minimizing sum of the maximum amount of shortages among the customers' zones in all periods. Working levels, workers productivity, overtime, subcontracting, storage capacity and lead time are also considered. Finally, the proposed model is solved as a single-objective mixed integer programming model applying the LP-metrics method. The practicability of the proposed model is demonstrated through its application in solving an APP problem in an industrial case study. The results indicate that the proposed model can provide a promising approach to fulfill an efficient production planning in a supply chain.

1. Introduction

Nowadays, supply chain management (SCM) which covers production planning for entire supply chain from the raw material supplier to the end customer has become the foundation for operations management. Since SCM has become the core of the enterprise management in the 21st century, there is a high interest to exploit the full potential of SCM in enhancing organizational competitiveness. SCM has a tremendous impact on organizational performance in terms of competing based on price, quality, dependability, responsiveness, and flexibility in the global market and it is becoming a more matured discipline. Hence, this requires a more defined organizational structure, performance measures, etc. One of the problems that should be addressed in this scope is aggregate production planning (APP), which is focused in this paper along with the broader topics of SCM. The SCM has made managers and analysts to shift their focuses from only manufacturing plant to entities plants interact with; for example, suppliers, warehouses, and customers. As a result SCM therefore, has recently received much attention (Dolgui and Ould-Louly, 2002; Wang and Liang, 2005; Gunnarsson and Rönnqvist, 2008; Lodree and Uzochukwu, 2008; Gebennini et al., 2009). Baykasoglu (2001) has defined APP as medium-term capacity planning over 3–18 months planning horizon and it determines the optimum production, workforce and inventory levels for each period of planning horizon for a given set of production resources and constraints. Such planning usually involves one product or a family of similar products with small differences so that considering the problem is justified from an aggregated viewpoint, and planners in the process of APP make decisions regarding overall production levels for each product category to meet the fluctuating demands in near future, also make policies and decisions relating to the issues of hiring, laying off, overtime, backorder and inventory. APP is an important technical level planning in a production management system. In the field of planning it falls between the broad decisions of long-range planning and the highly specific and detailed short-range planning decisions. Other forms of family disaggregation plans such as master production schedule, capacity requirements planning and

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material requirements planning all depend on APP in a hierarchical way (Ozdamar et al., 1998). APP has attracted considerable attention from both practitioners and academia (Shi and Haase, 1996). Numerous APP models with varying degrees of sophistication have been introduced in the last decades. Since Holt et al. (1955) proposed the approach for the first time; scholars have developed numerous models to help solving the APP problems, each with their own supporters and detractors. As a comprehensive remark, Nam and Logendran (1992) reviewed APP models from 140 journal articles and 14 books and categorized the models into optimal and near-optimal classifications. Hanssman and Hess (1960) developed a model based on the linear programming approach using a linear cost structure of the decision variables. Haehling (1970) extended the Hanssman and Hess (1960) model for multi-product, multi-stage production systems in which optimal disaggregation decisions can be made under capacity constraints. Masud and Hwang (1980) presented three MCDM methods, which were goal programming (GP), the step method and sequential multi-objective problem. These methods were applied to solve APP problem with maximizing profit, minimizing changes in workforce level, minimizing inventory investment and minimizing backorders. A set of data consisting of two products, a single production plant and eight planning periods was generated to compare the results. Goodman (1974) developed a GP model which approximates the original nonlinear cost terms of the Holt's model by linear terms and solves it using a variant of the simplex method. Baykasoglu (2001) extended Masud and Hwang's model with additional constraints such as subcontractor selection and setup decisions. A tabu search algorithm was designed to solve the pre-emptive GP model.

The APP can be considered as the combination of several classical production planning problems in the literature which has been modeled by some kinds of mathematical programming such as scheduling problems (Buxey, 1993; Foote et al., 1998), workforce planning problems (Mazzola et al., 1998) and long set up time problems (Porkka et al., 2003). However, if decisions are made based on the deterministic model, there is a risk that demand might not be met with the right products. It is an unfortunate reality that some critical parameters such as customer demand, price and manufacturing capacity are not known with certainty. If the supply chain designed by the decision makers is not robust with respect to the uncertain environment, the impact of performance inefficiency (e.g. delay) could be devastating for all kinds of enterprises. Since they cannot usually protect themselves completely against the risk, they have to manage it. Risk management can be used as a tool for greater rewards, not just control against loss. There are lots of papers to deal with enterprise risk management (see Wu and Olson, 2008, 2009a, 2009b, 2010a, 2010b; Wu et. al., 2010).

APP in many manufacturing environments is based on some parameters with uncertain values. Uncertainties might arise in product demand, etc. Thus, the robustness of a production plan in terms of fulfillment of product demand depends on incorporating the uncertain parameters in production planning models. Our research considers a supply chain problem under uncertainty of demands and various cost parameters. This implies that the problem is more realistic since demand and cost forecasts are seldom precise and in advanced forecasting systems they are usually given as more than a single value. Furthermore, due to demand uncertainty it may not be possible to meet all demands with their available capacity. The problem is introduced in details further.

Research that considers uncertainty can be categorized according to the four primary approaches (Sahinidis, 2004): (1) *Stochastic programming* approach, (2) *fuzzy programming* approach, (3) *stochastic dynamic programming* approach, and (4) *robust optimization* approach. In the first approach, some parameters are regarded as random variables with known probability distributions. The second one seeks the solution considering some variables as fuzzy numbers. The third one includes applications of random variables in dynamic programming which can be found essentially in all areas of multi-stage decision making. In comparison, the last one represents uncertainty through setting up different scenarios which demonstrate realizations of uncertain parameters. The aim of this approach is to find a robust solution which ensures that all specified scenarios are "close" to the optimum in response to changing input data.

As mentioned above, to deal with the real-world planning problems involving noisy, incomplete or erroneous data, the methods were employed in some cases such as stochastic programming (Kall and Wallace, 1994; Birge and Louveaux, 1997; Kall and Mayer, 2005); fuzzy set theory (Wang and Fang, 2000); robust optimization (Bertsimas and Sim, 2003, 2004, 2006; Ben-Tal and Nemirovski, 1998, 1999, 2000) and stochastic dynamic programming. The last one was used mostly in the past to obtain closed-form solutions of analytically tractable models and numerical solutions to relatively small problem instances. With the recent developments in approximations, especially neuro-dynamic programming, this methodology offers the potential of dealing with problems that for a long time were considered intractable due to either a large state space or the lack of an accurate model. Some applications have included: production planning (Cheng et al., 2003), and supply chain management (Bitran et al., 1998). Bakir and Byrne (1998) developed a stochastic LP model based on the two-stage deterministic equivalent problem to incorporate demand uncertainty in a multi-period multi-product (MPMP) production planning model. In Escudero et al. (1993) a multi-stage stochastic programming approach was proposed for solving an MPMP production planning model with random demand. It is important to note that stochastic programming approach focuses on optimizing the expected performance (e.g. cost) over a range of possible scenarios for the random parameters. We can expect that the system would behave optimally in the mean sense. However, the system might perform poorly at a particular realization of scenarios such as the worst case scenario. More precisely, unacceptable inventory and backorder size for some scenarios might be observed by implementing the solution of two-stage stochastic model. The solutions in the form of fuzzy number provide different conditions to the production management in an uncertain environment. Tang et al. (2000) introduced a novel approach to modeling multi-product APP problems with fuzzy demand and fuzzy capacities. The objective of the considered problem was to minimize the total costs of quadratic production costs and linear inventory holding costs. Tang et al. (2003) proposed an approach that focuses on a formulation and simulation analysis for multi-product APP problems with fuzzy demands and fuzzy capacities. The fuzzy multi-product APP model was transformed into a parametric programming model. A simulation of a practical instance was conducted to illustrate the model and demonstrate the performance and effect of various parameters on the optimal APP. Wang and Fang (2001) extended a four-objective APP model defined by Masud and Hwang (1980) with fuzzy parameters such as fuzzy demand, fuzzy machine time, fuzzy machine capacity and fuzzy relevant costs. Wang and Liang (2004) developed a fuzzy multi-objective linear programming model for solving a multi-product APP decision problem in a fuzzy environment. Also Aliev et al. (2007) developed a fuzzy integrated multi-period and multi-product aggregate production and distribution model in supply chain. The model was formulated in terms of fuzzy programming and the solution was provided by genetic algorithm.