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A robust hierarchical production planning for a capacitated two-stage production system

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ABSTRACT

In this paper, we propose a robust hierarchical production planning approach for a two-stage real world capacitated production system operating in an uncertain environment. The first stage of the system produces a set of semi-finished products having relatively stable annual demands, and the second finishing stage produces finished products having highly variable weekly demands. The fixed production setup costs incurred at the first stage are considerably high. Fixed production setup costs incurred at the second stage are fairly small compared to those of the first stage. We propose an integrated hierarchical planning model, where semi-finished products from the first stage (i.e. the aggregate level) are disaggregated into finished products to be produced in the second stage (i.e. the operational level). As a result of the relatively stable demands and the high setup costs experienced at the first stage, a cyclical aggregate planning model is proposed for production planning at the upper level of the hierarchical plan. Based on this aggregate plan, a modified periodic review policy is then proposed for production planning at the lower level. Finally, a coupling plan, linking the two planning levels, is proposed to ensure the feasibility of the disaggregation process at every period.

1. Introduction

The two-stage production system discussed in this paper is a real world production process having some particular features which, if taken into account in the planning process, may unequivocally lead to effective production plans. The first stage of the production system produces some 200 different semi-finished products which are either shipped directly in this current status to other manufacturers or processed further in the second stage to produce some 10,000 different finished products. Therefore, production plans developed for the first stage can naturally be considered as aggregate production plans (i.e. the aggregate level), which can subsequently be disaggregated to provide plans for the second stage (i.e. the operational level). The first special feature of the production system is that fixed production setup costs experienced at the first stage are significantly higher than those experienced at the second stage. This fact differs from the usual hierarchical production planning processes which consider that fixed costs at the aggregate level are negligible and take these costs into account only at the detailed level (i.e. the operational level). In addition, as it is often the case in almost all manufacturing systems, it is difficult to accurately forecast finished product demands. This is what usually makes aggregate plans less effective in practice. The second special feature is related to the fact that demands of the semi-finished products are relatively stable, due to the strong position of the manufacturers in the semi-finished product market. Moreover, the variability of the finished product demands can be approximated by looking back into the past demand realizations.

The main objective of this research is to develop a robust hierarchical production planning approach for the two-stage production system, which explicitly considers those special features during the planning process. The production planning approach also takes the variability of finished product demands into account, which consequently generates plans for the whole system that are robust (i.e. less sensitive to the demand variability).

The proposed planning approach is based on the hierarchical production planning approach presented by Bitran and Hax (1977), which benefits are well-established in the literature (see also Bitran, Haas, & Hax, 1981, 1982). In a typical hierarchical production planning model, the objective is mainly to decompose a large and complex planning problem into less complex planning sub-problems resulting in consistent aggregate and master production schedules. In the production system at hand, the fact that demands of semi-finished products are relatively stable suggests that, even though demands of the finished products are random, planning at the level of semi-finished products may have some stabilizing effect on the aggregate production planning of the whole system.

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The remainder of this paper is organized as follows. Section 2 provides a brief review of the literature. In Section 3, we describe and formulate the two-stage production planning problem. Section 4 presents and discusses an alternative robust planning approach. Section 5 provides an extensive analysis of the approaches and presents related computational results. Finally, some concluding remarks are given in Section 6.

2. Literature review

Developing aggregate production planning models and their corresponding solution approaches has been, and still is, an area of active research since the seminal work of Wagner and Whitin (1958). There exists a vast literature discussing lot-sizing problems and related solution approaches when the critical production planning parameters such as demands, lead times, and costs are deterministic. A comprehensive literature review addressing these deterministic lot-sizing problems can be found in Bahl, Ritzman, and Gupta (1987), Drexl and Kimms (1997) and Jans and Degraeve (2008). When these parameters are stochastic, the resulting lot-sizing problems become more challenging since they also include the complexity of their deterministic versions. Bitran and Yanasse (1984) discussed a stochastic single item lot-sizing problem and proposed a deterministic equivalent for it, incorporating a stockout probability constraint. They showed that the relative error bound is small enough, which justifies its practical use. Bookbinder and Tan (1988) have considered an uncapacitated single item lot-sizing problem with stochastic demands, also incorporating a service level constraint on the probability of a stockout. They proposed a static–dynamic uncertainty strategy, where the replenishment periods are fixed at the beginning of the first period, while the lot sizes are determined dynamically based on the known demands for all periods since the most recent production decision. Their model is later extended by Tarim and Kingsman (2004) to include unit variable purchase/production costs. They showed that in case of non-zero variable costs, the problem cannot be treated as a stochastic form of the Wagner–Whitin problem. Finally, a study by Axsater (1996) showed an error bound of approximately 0.1180 if the deterministic EOQ (Economic order quantity) is used as a heuristic to solve the stochastic lot-sizing problem.

Robust optimization models (see e.g. Leung & Wu (2004)) based on the approach proposed by Mulvey, Vanderbei, and Zenios (1995) has been used to generate aggregate plans. Mulvey et al. (1995) modified the Markowitz two-stage stochastic model by adding a measure of variability of the objective function of the second stage to the objective function considered at the first stage level. Depending on the weight put on this variability measure, the optimization process may favor solutions with lower expected values in trade for a lower expected second stage deviation. Mulvey et al. (1995) refer to this paradigm as robust optimization. This robust optimization approach has been used for capacity planning of power systems (Malcom & Zenios, 1994), for chemical-process planning under uncertainty (Ahmed & Sahinidis, 1998) and for telecommunications network design (Bai, Carpenter, & Mulvey, 1997; Laguna, 1998). Velagapudi and Ghosh (1989) discussed the issue of robustness in automated batch manufacturing systems. The authors proposed a robust planning and scheduling model which combines preparation and implementation of plans along with learning from system's own experience. Also, Kleijnen and Gaury (2003) considered a production-control study, and define robustness as the capability to maintain short-term service under a variety of scenarios. They presented a stage wise method, which combines simulation, optimization, risk or uncertainty analysis, and bootstrapping techniques to achieve robust solutions.

In addition to the stochastic and robust optimization models for stochastic lot-sizing problems thoroughly discussed in the literature, various researchers such as Ari and Axsäter (1988), Lasserre and Merce (1990), Gfrerer and Zapfel (1995), Raa and Aghezzaf (2005) and Aghezzaf et al. (2010) have investigated the idea of integrating variability of some critical production planning parameters in the process of developing robust production planning systems. In particular, the issue of developing deterministic robust aggregate planning models within a hierarchical production planning framework is investigated. A robust aggregate plan is defined as a plan that results in at least one feasible disaggregation for any demand realization. The model proposed by Gfrerer and Zapfel (1995) assume that the demand of each product family is known (deterministic) but the demands of the finished products may take any values between known demand lower and upper bounds. In this paper, we take advantage of the fact that demands of the semi-finished product can be considered as deterministic. The resulting aggregate plan is then used to generate robust plans for the whole system taking into account the variability of the finished product demands.

3. Problem description and formulation

Consider the two-stage production process depicted in Fig. 1. An Example of such production setting corresponds with Agfa's manufacturing process for X-ray film. The first stage is a coating department, where a photographic emulsion is coated on base rolls, producing master-rolls of medical and other applications films. In the second stage these master-rolls (semi-finished products) are cut into a large number of finished products, different in size and packaging format, and shipped to the final consumers. A large part of these semi-finished products are produced on a Make-To-Stock (MTS) basis and stored to feed the finishing department (the second stage). Only few semi-finished products are produced and delivered directly to customers on a Make-To-Order (MTO) basis. For simplicity, the MTO demands is not included in the current model as their contribution to the total demand is marginal and are manufactured upon receipt of customers orders (i.e. the setup

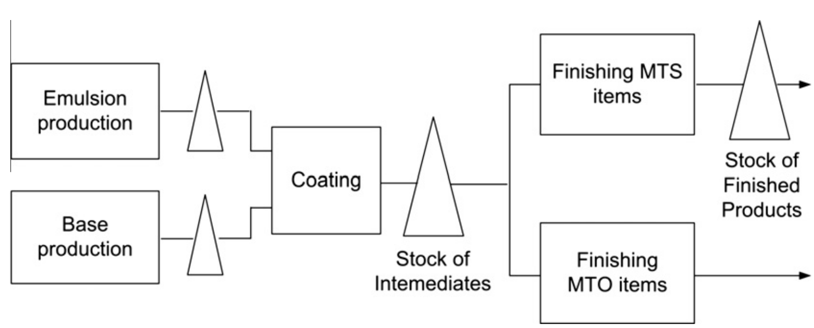

Fig. 1. A two-stage production process (adapted from Van den Broecke et al. (2005)).