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Integrated production planning with sequence-dependent family setup times

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ABSTRACT

This paper proposes an integrated optimization model of aggregate production planning (APP), family disaggregation planning, and family scheduling problems in hierarchical production planning (HPP) systems considering sequence-dependent family setup times. The model obtains the optimal production plan for each product type and product family in each period, together with the globally optimal production sequence of product families in all planning periods. The proposed model is tested with randomly generated experimental data consistent with what is prevalent in the manufacturing industry and its results are compared with those of the traditional HPP models. Our results show that the integrated model realizes greater cost savings.

1. Introduction

Production planning problems are generally formulated in one of two ways: monolithic and hierarchical. The monolithic approach (Manne, 1958; Lasdon and Terjung, 1971) formulates the problem as a mixed integer linear programming model for all items. However, this level of detail in the formulation of the problem requires demand data that is difficult to forecast accurately and is expensive to implement (Bitran et al., 1981).

On the other hand, the hierarchical approach (Hax and Meal, 1975) decomposes the problem into several layers of sub-problems corresponding to different product structures, including APP for product type, family disaggregation planning for product families, and item disaggregation planning for items. Product types are groups of items having similar unit costs, direct costs (excluding labor), holding costs per unit per period, productivities, and seasonalities, while product families are groups of items pertaining to the same type and sharing similar setups (Bitran et al., 1981). Since the sub-problems can be solved much more easily, the hierarchical approach may meet managers' needs for a quick solution than a monolithic approach. Moreover, the fact that there are usually a small number of types justifies the use of sophisticated forecasting techniques that may be expensive to employ for thousands of items (Bitran et al., 1981).

However, the hierarchical planning approach suffers from several weaknesses. First, its hierarchical sub-problems should correspond to the organizational and decision-making echelons in the firm, resulting in increased interaction between the planning system and the decision-makers at each level (Graves, 1982). But organizational structures are becoming increasingly flatter, calling into question the utility of HPP models with rigid structures.

Second, the family setup costs and times, determined at the second level family disaggregation models but influencing the top level models, are not taken into account in the aggregate decisions. Consequently, the resulting production plans are not necessarily optimal and susceptible to loss of cost savings opportunities, since a near-optimal aggregate plan may lead to much lower setup costs than an optimal one. Also the obtained production plans may be infeasible because the family setup times in the family disaggregation model inevitably consume the production capacity, which should have been assigned to produce the types in APP decisions. Therefore, when family setup costs and times are not trivial (Qiu et al., 2001; Yalcin and Boucher, 2004; Omar and Teo, 2007; Pastor et al., 2009) as in some manufacturing industries, their influences on the optimality and feasibility of the aggregate plans, and consistency when the aggregate plans are disaggregated, have to be considered.

Third, the total family setup time in the planning horizon, usually calculated by summing up the optimal setup time in each period, is not necessarily globally optimal when the sequence dependencies between different families are considered. Due to the sequence dependency, the optimal schedule in the planning horizon is not only determined by the families produced in each period, but by the initial machine status in each period.

To alleviate these weaknesses we propose a model that integrates APP problem and family disaggregation planning and scheduling problems with sequence dependent setup times and costs, and considers the global family scheduling optimization in

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the planning horizon. First, the model is robust enough to fit different organizational structures, providing flexibility for the decision maker. This is because it cannot only plan the production and scheduling of types for top-level managers, but also decompose the aggregate plans into detailed production plans of families for mid-level managers, and even provide scheduling information for the scheduling staff on the shop floor. When the organizational structures become flatter, managers at each layer can easily extract the relevant information (production plans of types or families) they need from the model. Second, the infeasibility of aggregate plans due to capacity consumption by family setup times can be eliminated. The model also maintains consistency when aggregate plans are disaggregated, and ensures the optimality of the production plans and schedules, or as close to optimal as possible. Third, the globally optimal family schedules in all periods of the planning horizon are concatenated to form an optimal schedule, rather than optimizing them period by period. The latter sequential family scheduling is more likely to be trapped in a local optimum, since the schedule in one period may result in an inferior schedule in the subsequent period.

The remainder of this paper is organized as follows. In Section 2, the related literature is reviewed. In Section 3 a representative traditional HPP system by Ozdamar et al. (1998) is presented. Section 4 formulates the proposed integrated model. In Section 5, the corresponding benchmark problems of the proposed integrated approach are presented. The performance of the integrated model is validated with randomly generated experimental data in Section 6, together with some managerial implications of the study. We discuss the conclusions and future research directions in Section 7.

2. Literature review

When evaluating HPP systems, two approaches are often used. First, three crucial factors are of interest. *Consistency* requires that the constraints from upper-level plans imposed on the lower-level plans be satisfied. *Feasibility* requires that the plan at each level be practical. And, *optimality* requires that the total cost of the obtained production plans and schedules in all layers be globally optimal. Second, five elements (anticipation, instruction, reaction, implementation, and ex post feedback) proposed by Schneeweiss (1995) to evaluate the hierarchical interdependence within an organization, can be employed to assess HPP systems, since their APP and family disaggregation planning interact in a hierarchical way. Schneeweiss and Zimmer (2004) apply the hierarchical coordination mechanisms to the global optimization of the supply chain between a producer and a supplier.

Due to the appealing features of the hierarchical approach, a number of authors have studied the efficacy of HPP systems, after the pioneers Hax and Meal (1975). Bitran et al. (1981) present a typical HPP approach to plan and schedule production for single stage manufacturing environments. Axsater (1986) describes constraints on the aggregate level types that will guarantee the existence of a feasible disaggregation at the lower level. Bowers and Jarvis (1992) propose a three-tiered hierarchical model with a product grouping procedure that is designed to implicitly minimize sequence-dependent setup time. McKay et al. (1995) review prior research and provide a guide to configure different HPP systems for different real-life environments. This guide facilitates the development of hierarchical planning and its wide use in practice. Ozdamar et al. (1998) propose a decision support system for HPP in order to facilitate the production planning task for end-users by providing an easy-to-use tool. Yalcin and Boucher (2004) propose a continuous-time algorithm to disaggregate the aggregate production plans so that individual families are scheduled for production on shared resources. Neureuther et al. (2004) propose a three-tiered HPP for a make-to-order steel fabrication facility in order to develop a production plan and master schedule for a set of the so-called "product archetypes", classified by class as industrial or commercial, or by type as angle, beam or plate, or by weight as light or heavy.

The above approaches make sense only when setup costs and times are negligible. Therefore, they cannot guarantee global optimality and feasibility when family setup times are considered. From the perspective of the hierarchical interdependence, *instruction*, *implementation*, and *ex post feedback* are achieved, while *anticipation* and *reaction* are not considered.

At the APP level, Qiu and Burch (1997) introduce the concept of expected setup cost (ESC) to anticipate the sequence-dependent setup costs at the family disaggregation level. Although the ESCs are not necessarily optimal, the influence of the anticipation element is recognized in the model to some extent. When tested with actual plant data, Qiu et al. (2001) find that the HPP–ESC model outperforms prior HPP models, especially the model proposed by Bowers and Jarvis (1992). Some improved degree of optimality brought about by the ESC and consistency are ensured in both models. However, the setup times and their influence on production capacity are still not considered, which may challenge the feasibility of the obtained aggregate plans. Moreover, the suboptimal setup costs may also negatively affect optimality of the aggregate plans. From the interdependence point of view, the only drawback of the above two models is that they ignore the reaction element. In the HPP system proposed by Rohde (2004), the anticipation function provides knowledge of the base level to the top-level in terms of approximate setup times per period. The effect of setup times from the base level is considered and therefore the feasibility of the HPP system is ensured to some degree. However, the HPP system does not consider setup costs in the top-level planning model, so the optimality of the entire system cannot be guaranteed.

Graves (1982) integrates the family disaggregation model with sequence independent setup costs into the APP model, but setup times are not considered. Omar and Teo (2007) propose a hierarchical model for multi-product batch chemical plants, integrating the corresponding setup times and costs into the capacity constraints and objective function of the APP model in order to ensure feasibility and optimality of the production plans. However, sequence dependencies between families are not considered. Moreover, it is questionable whether their hierarchical system can be applied to other industries.

Soman et al. (2004) propose a conceptual HPP framework for MTO (make-to-order) and MTS (make-to-stock) production situations, where only the MTO products with the same color are aggregated into a family to reduce solution complexity. However, the influence of lower level setup costs and setup times is not considered in mid-term production plans.

In the recent past, interest has focused on the integration of production planning and other manufacturing features such as maintenance (Wienstein and Chung, 1999; Aghezzaf et al., 2007; Dehayem Nordem et al., 2009), scheduling (Jozefowska and Zimniak, 2008), plant capacity planning (Hsu and Li, 2009), product safety related traceability factor (Wang et al., 2010), process planning (Li et al., 2010), and cell formation (Ah kioon et al., 2009; Safaei and Tavakkoli-Moghaddam, 2009). The integration brings about huge computational efforts partly due to the monolithic production planning for all items.

3. Traditional HPP model

Ozdamar et al. (1998) propose a Hierarchical Decision Support System for production planning, encompassing aggregate planning