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A multi-criteria master production scheduling approach for special purpose machinery

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ABSTRACT

This paper presents a multi-criteria master production scheduling approach as the final assembly of special purpose machines is known to be very cost intensive. These costs are mainly influenced by the master production schedule (MPS). Two major cost drivers arise. First, long assembly lead-times (up to several months) combined with high product values result in high capital commitments; thus, lead-times need to be minimized. Moreover, the factory calendar must be considered while calculating the MPS because the factory calendar can significantly influence the resulting lead-times. Second, contractual penalties and compensation costs arise if confirmed delivery dates cannot be kept. Therefore, resource requirements must be accounted for, and an MPS that is executable on the assembly shop floor must be calculated. To increase planning flexibility, we do not restrict the resource utilization with a formal constraint; instead, we introduce the additional objective of resource leveling. Consequently, the conflicting objectives lead-time minimization and resource leveling are integrated into a single objective function, in which the decision maker's preferences are represented by a weighting factor. To calculate such an MPS, we develop a tailor-made construction heuristic combined with a randomized variable neighborhood descent procedure. We evaluate our solution method by solving small instances with a commercial solver and large-scale instances from an application case of an aerospace company. Our results reveal that the decision maker's preferences are adequately reflected by the weighting factor. Moreover, we can provide a rule of thumb for selecting an appropriate initial weighting factor.

1. Introduction

The master production scheduling problem addressed in this paper is based on an application case that originated in the aerospace industry. As many German machine and plant manufacturers have done, the company has reacted to the challenges resulting from globalization and changed market relations by individualizing and segmenting its products and services. The company now offers complex, customer-specific top-level products (also called special purpose machines) for certain markets. To provide customer-specific products within competitive delivery times, special purpose machines are manufactured using an assemble-to-order (ATO) strategy, whereas the assembly itself is organized as a series production. This ATO strategy and several characteristics of the product and assembly process make the final assembly the main focus of interest in achieving two fundamental goals: cost reduction and customer satisfaction. The effect of the final assembly on these two goals can be explained in two ways. First, long assembly lead-times (up to several months) combined with a high product value (up to several million Euros) lead to high capital commitments. The long assembly lead-times result from a high level of manual assembly effort, which is driven by the use of cutting-edge technology and the high complexity of the product. Second, the final assembly is directly linked to customer delivery and thus has a direct impact on customer satisfaction.

According to Vieira and Favaretto (2006), master production scheduling (also called master planning (MP); Rhode and Wagner, 2008) "[…] is a key decision-making activity, in which strategic goals from business planning are translated into an anticipated statement of production, from which all other schedules at lower levels are derived". The importance of MP becomes obvious when the interdependencies with other planning tasks in a hierarchical production planning system (HPPS) are analyzed, as affirmed by several authors (e.g., Vollmann et al., 2005; Rhode and Wagner, 2008). According to these authors, MP is the basic input for dependent planning tasks, such as capacity planning, production planning and scheduling, distribution and transport planning, sales planning, order promising or purchasing, and material requirements planning. The importance of MP is also noted in several publications on customer-oriented individual production and ATO, such as Drexl et al. (1994), Franck et al. (1997), and Hans et al. (2007).

The general task of MP that is pertinent to this paper is the determination of a master production schedule (MPS). An MPS is a

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temporal framework that coordinates dependent planning tasks and the flow of materials. On the basis of this function and the characteristic planning environment of special purpose machinery, we define the determination of assembly start and completion dates for assembly orders as the basic task of MP. In contrast to other approaches concerning MP, we do not integrate additional planning tasks, such as material requirements planning, into our analysis because the required information is not available at the time of planning.

As MP has such an important coordination function and "the objective function drives the logic behind the execution" (Vieira and Favaretto, 2006), both fundamental goals must be represented by the planning objectives. In terms of cost reduction, an optimized MPS can influence capital commitments. Cost reduction is primarily achieved through lead-time minimization. Concerning the planning problem at hand, the lead-time can only be improved if factory calendars (also called break calendars; cf. Trautmann, 2001) significantly influence the planning result. This influence is important for the underlying MPS problem and also other scheduling problems, such as "[…] real-life projects, make-to-order production, or process flows in the chemical industries, […]" (Neumann et al., 2003). Generally, scheduling with break calendars is termed calendarization (introduced by Zhan (1992)) and is addressed, for example, by Schwindt and Trautmann (2000) and Franck et al. (2001). Calendarization contributes to customer satisfaction because shorter assembly lead-times reduce customer delivery times. Other significant cost factors are contractual penalties and compensation costs, which are directly linked to the second goal of customer satisfaction, particularly the objective of high delivery reliability. As customer satisfaction cannot be directly influenced by MP (confirmed delivery dates do not exist at the time of planning), resource leveling is defined as a surrogate objective. The purpose of resource leveling is to support the operability of the MPS on the assembly shop floor and thus to enable on-time delivery. Moreover, resource leveling allows workforce adjustment costs to be reduced or even completely avoided. To address these conflicting objectives, namely, lead-time minimization and resource leveling (the conflict will be discussed in the following sections), we developed a multi-criteria master production scheduling approach.

As the following section will show, the existing literature does not sufficiently address the problem at hand; therefore, a new planning approach is required.

2. Literature review

Capital commitments are one of the main cost drivers in the production of special purpose machinery; thus, their reduction is the primary objective of MP. However, these costs are directly linked to work-in-process inventory costs, and they are very difficult to assess because of the vast number of materials and their time of assembly. Therefore, an operational surrogate objective is used: lead-time minimization (or throughput time minimization – cf. Pinedo, 2009). In the literature, many different criteria are used to evaluate lead-time performance. Examples include the sum of (weighted) lead-times, mean (weighted) lead-time, maximal lead-time, sum of deviations, and mean deviations. Note that the first two criteria listed are pairwise equivalent. In addition, the maximal lead-time criterion is not suitable because only orders with long net lead-times would be affected by the optimization. Moreover, to our knowledge, no comprehensive study comparing these objectives exists; thus, no objective is claimed to be superior to the others. As a consequence, the suitable criterion depends on the specific problem and the decision maker's preferences. In this paper, the objective of lead-time minimization is represented by a lead-time deviation criterion that is equivalent to minimizing the mean lead-time.

The objective of resource leveling (also called resource balancing or resource smoothing) has gained increasingly more attention in recent years (cf. Anagnostopoulos and Koulinas, 2010; Drótos and Kis, 2011; Gather et al., 2011). Comprehensive introductions to this topic can be found in Younis and Saad (1996), Neumann and Zimmermann (1999), Caramia and Dell'Olmo (2006), and Ballestín et al. (2007). Anagnostopoulos and Koulinas (2010) state that the "[…] scheduling objective of resource leveling is to make the resource requirements as even as possible over the entire project horizon, usually, without explicit resource considerations to be taken into account". This statement is consistent with Drótos and Kis's (2011) statement that "in resource leveling problems the objective is to minimize a function of the resource utilization over time". Typically total squared utilization costs are minimized to achieve balanced resource utilization (Gather et al., 2011). Neumann and Zimmermann (1999) analyze the suitability of three different objective function classes for projects with minimum and maximum time lags. Following these contributions and the requirements of the underlying planning problem, we use a criterion defined as the root ("normalized") of the sum of squared deviations from a desired value to balance resource utilization. This function is used because it explicitly penalizes strong deviations.

Concerning conflicting objectives, a vast number of methods to solve conflicts exist in the literature (introductions, overviews, and details of these methods can be found e.g., in Gupta et al. (1991), Dyer et al. (1992), Keeney et al. (1993), Kirkwood (1997), Belton and Stewart (2002), Hoogeveen (2005), Figueira et al. (2005), or T'kindt and Billaut (2006)). Here, the challenge is to evaluate the different methods of multi-criteria decision analysis, multi-criteria decision making, multi-objective decision making (MODM), or multi-attribute decision making (MADM) with regard to their applicability and suitability for the given decision problem. As the number of general topics about decisions with multiple objectives suggests, this challenge may be substantial. A tentative guideline for method selection is given in Guitouni and Martel (1998). A first distinction can be made by the determination of alternatives (problem solutions). As an explicit determination of (discrete) alternatives is not applicable for the problem at hand, only methods with an implicit determination are of interest (this type of method is often categorized as an MODM method and is also called multiobjective programming (MOP); cf. Ehrgott and Gandibleux, 2000). One can also distinguish between methods where the (final) decision is made a posteriori or a priori. The a posteriori methods are based on a set of compromise solutions and their attributes (MADM; sometimes also called generate-first–choose-later or construction and exploitation methods). Some a posteriori methods are outranking-based methods or methods based on multi-attribute utility/value theory (cf. Dyer, 2005). The a priori methods have a single compromise solution, and the decision maker specifies his preferences concerning the objectives before solutions are calculated; thus, his preferred compromise solution is already specified. Some commonly used a priori methods are hierarchical optimization (also called lexicographical ordering), objective dominance, objective weighting, and goal programming.

With regard to the planning problem at hand, we use a MODM/MOP-based approach that integrates the lead-time minimization and resource leveling objectives into a single objective function. This objective function consists of two components (one for each of the objectives) that each measure deviations (similar to the goal programming approach) and normalize the deviations by adjustment factors (cf. Vieira and Favaretto, 2006). After normalization, the objective function combines the deviations additively and