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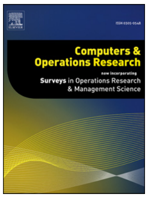

Production planning with order acceptance and demand uncertainty

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ABSTRACT

Traditional production planning models assume that all orders must be satisfied when capacity is available. In this paper, we analyze the value of providing decision makers with the flexibility to accept or reject orders, when order quantity is uncertain. We introduce this demand flexibility in two production planning problems. The first problem integrates order acceptance in the capacitated lot sizing problem, providing the option to reject an order if it requires a high setup cost and cannot be aggregated with additional orders to take advantage of economies of scale. The second problem integrates order acceptance in the order release planning problem with load-dependent lead times (LDLTs). This problem provides the option to reject an order if it increases the workload causing the delay of other orders due to congestion effects. Robust counterparts of both integrated problems are formulated as linear mixed integer programs (MIPs). The deterministic integrated problems and their robust counterparts are shown to be NP-hard and a two-stage MIP heuristic is proposed as a solution procedure. A relax and fix (RF) heuristic is adapted to efficiently construct feasible solutions to the robust problems, which are then improved by a fix and optimize (FO) heuristic. Numerical results show that the proposed heuristics give promising results in terms of solution quality and computation time. Simulation experiments are conducted to assess the value of demand flexibility and to study the effects of various parameters on economical performance.

1. Introduction

Classical production planning models determine the production plan with minimal cost or maximal profit given that demand must be satisfied when capacity is available. Demand for each period is the aggregate of customer orders with the same due date. However, it is often necessary to differentiate customer orders for several reasons (Aouam and Brahimi, 2013). In fact, different custumers might impose particular conditions on the source of raw materials or on the quality control tests made during the manufacturing process of their orders. Also, in the case of limited capacity, the decision maker can only satisfy demands partially and consequently has to decide which customer orders to satisfy. In addition, even if there is enough capacity to satisfy all orders, we distinguish two operational reasons for potentially rejecting an order: economies of scale and congestion effects. These two reasons are explained next, leading to two integrated order acceptance and production planning problems.

The first reason for rejecting an order is related to economies of scale, which are traditionally modeled in the lot sizing problem (Wagner and Whitin, 1958). The lot sizing problem balances between setup and inventory costs, while satisfying demand in each period. However, It might be more profitable for a firm to reject an order if it requires a high setup cost and cannot be aggregated with additional orders to justify the production setup (Geunes, 2012). The second reason is due to congestion effects. Production lead time, i.e., the time required for material released into the production system to be transformed into finished goods, depends on the workload. Queuing models have revealed that lead time increases non-linearly as the resource utilization approaches 100% (Hopp and Spearman, 2001). Congestion effects are usually modeled using clearing functions in the order release planning problem with load dependent lead times (LDLTs) (Asmundsson et al., 2006), where all demand must be satisfied. However, the more orders are accepted the higher are the production lead times, resulting in the possibility of missing customer due dates. This can also have an economical interpretation. In fact, Kefeli et al. (2011) show that the marginal prices of capacitated resources are not necessarily equal to zero when the utilization is less than one. This means that even in the case where capacity is available, the revenue from an additional order should at least offset the variable production

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cost plus the dual of the capacity constraints that take workload into account.

Demand uncertainty is a critical factor to consider in production planning, especially for manufacturers with long production lead times. Specific customer orders are subject to great uncertainty in terms of order size and due date. In the case of semiconductor manufacturing for example, customers provide a demand signal (an indication of what their orders will ultimately be), well in advance of the due date, and as time evolves they gradually adjust their orders until a firm order is obtained. Despite the magnitude of change between the demand signal and the firm order, customers still require that orders be met within a short period from their eventual due date (Higle and Kempf, 2011). Order quantity uncertainty can also be contracted through quantity flexibility contracts where a manufacturer allows the buyer to modify the order (within limits) after observing demand (Bassok and Anupindi, 1997; Tsay and Lovejoy, 1999). Demand uncertainty affects production planning and order acceptance decisions as both economies of scale and workload are affected by the actual size of accepted orders.

Stochastic optimization methods have been applied to multi-period production planning problems with demand uncertainty, (Aouam and Uzsoy, 2012; Mula et al., 2006). The two most popular frameworks are stochastic programming (Birge and Louveaux, 2011) and robust optimization (Bertsimas and Sim, 2004) since they have undergone significant advances, raising the possibility of their use to efficiently provide high-quality approximate solutions. The robust optimization approach has two main advantages compared to traditional stochastic programming approaches: (i) the robust counterpart preserves the complexity of the nominal problem and remains computationally tractable, independently from the number of uncertainty parameters. On the other hand, the number of scenarios grows exponentially with the number of parameters in stochastic programming, therefore presenting a computational challenge. (ii) The precise knowledge of the probability distributions of uncertain parameters is not required in robust optimization, whereas stochastic programs require the probability distributions of uncertain parameters for generating the scenarios. We deal with uncertainty in order quantities by applying robust optimization to find a trade-off between optimality and robustness of the solution.

Consider a capacitated production stage with a set of orders, placed in advance of the planning horizon, and the planner must determine which orders to accept as well as a production plan for satisfying these orders over a finite horizon. Each order is characterized by a delivery period and an order quantity that is uncertain, i.e. can vary between an upper and lower limit without knowledge of the probability distribution. Revenue is generated from accepted orders and backordering is allowed at a cost. At the beginning of the planning horizon, an order is either accepted in full or rejected, i.e., fractional acceptance is not allowed. The paper formulates integrated models that incorporate order acceptance into traditional production planning problems providing the planner with demand flexibility.

Two types of models are introduced, the first type integrates order acceptance in a capacitated lot sizing problem, providing the option to reject an order if it requires a high setup cost and cannot be aggregated with additional orders to take advantage of economies of scale. In this model, it is assumed that the production quantity in a given period can be as high as the available capacity regardless of the current work-in-process level at the shop floor. In production planning, this is the most commonly used production capacity model, (Brahimi et al., 2017). The second type integrates order acceptance in an order release planning problem with load-dependent lead times (LDLTs), which can be considered at an aggregate level of production planning. Ignoring the effect of congestion at the higher planning level leads to an overestimation of resource capacity, leading to an infeasible production plan. While this model assumes negligible setup costs, it takes into account congestion effects at the shop floor by relating WIP levels to production quantities, (Graves, 1986; Karmarkar, 1989). This model provides the option to reject an order if it increases the workload causing the delay of other orders.

This paper develops robust optimization formulations for the two integrated production planning and order acceptance problems in order to reflect the effects of demand uncertainty. These models are evaluated by means of a simulation study, based on profits and fill rate. Experiments illustrate that there is value in integrating production planning and order acceptance decisions, as well as considering uncertainty. In addition, we show that the formulated integrated problems and their robust counterparts are NP-Hard and propose an efficient two-stage MIP heuristic (RFFO) to solve these problems. In phase I, a relax and fix (RF) heuristic decomposes integer production and order acceptance variables based on time periods. For the robust models, when the number of periods or the number of orders is large, the solution of the MIP subproblems remain computationally expensive. To tackle this issue, the MIPs in each RF iteration consider part of the problem to be deterministic by truncating uncertainty after a certain number of periods. This adapted RF leads to better and faster solutions when compared to the traditional RF. These feasible solutions are then improved in phase II using a fix and optimize (FO) heuristic. Numerical results show that the proposed solution algorithm provides better quality solutions in reasonable computation times when compared with a state-of-the-art mixed integer programming solver.

The remainder of the paper is organized as follows. Section 2 discusses related work and highlights the contribution of the paper. In Section 3, integrated deterministic models are presented and their robust counterparts are formulated in Section 4. Section 5 establishes the complexity of the problems and discusses a two-stage MIP solution procedure. Economical and computational numerical experiments are conducted in Section 6. Section 7 concludes the paper and provides future research directions.

2. Related work

Order acceptance decisions are often treated separately from production planning. Typically, the sales department decides on order acceptance while the production department is responsible for production planning. If the goal of the sales department is to maximize turnover, it would simply accept as many orders as possible and neglect capacity constraints (Ebben et al., 2005). On the other hand, if capacity is taken into account but no planning is performed, the problem can be regarded as a knapsack problem, which describes how to determine the most valuable combination out of a given set of possibilities (Kleywegt and Papastavrou, 2001). With this approach, due dates of certain orders would be missed leading to penalties. ten Kate (1994) investigated order acceptance in production planning using two approaches: a hierarchical approach and an integrated approach. The hierarchical approach focuses on finding the best order and subsequently planning this order in an optimal way, given a certain set of already accepted orders. The integrated approach finds simultaneously an optimal production plan for a set of selected orders. This approach was proven to perform better in the case of a high load fraction (resource utilization) and short lead time (time between order and delivery).

Limited work integrates lot-sizing and order acceptance, (Geunes, 2012; Zhai, 2011). Geunes et al. (2005) and Merzifonluoğlu and Geunes (2006) examine demand selection and setup decisions, where they consider uncapacitated and fractional