European Journal of Operational Research 216 (2012) 334–345

Contents lists available at SciVerse ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Production, Manufacturing and Logistics

Managing capacity flexibility in make-to-order production environments

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ARTICLE INFO

Article history:
Received 13 August 2009
Accepted 25 July 2011
Available online 2 August 2011

Keywords:
Supply chain management
Capacity flexibility
Stochastic programming
Make-to-order
Assignment

ABSTRACT

This paper addresses the problem of managing flexible production capacity in a make-to-order (MTO) manufacturing environment. We present a multi-period capacity management model where we distinguish between process flexibility (the ability to produce multiple products on multiple production lines) and operational flexibility (the ability to dynamically change capacity allocations among different product families over time). For operational flexibility, we consider two polices: a fixed allocation policy where the capacity allocations are fixed throughout the planning horizon and a dynamic allocation policy where the capacity allocations change from period to period. The former approach is modeled as a single-stage stochastic program and solved using a cutting-plane method. The latter approach is modeled as a multi-stage stochastic program and a sampling-based decomposition method is presented to identify a feasible policy and assess the quality of that policy. A computational experiment quantifies the benefits of operational flexibility and demonstrates that it is most beneficial when the demand and capacity are well-balanced and the demand variability is high. Additionally, our results reveal that myopic operating policies may lead a firm to adopt more process flexibility and form denser flexibility configuration chains. That is, process flexibility may be over-valued in the literature since it is assumed that a firm will operate optimally after the process flexibility decision. We also show that the value of process flexibility increases with the number of periods in the planning horizon if an optimal operating policy is employed. This result is reversed if a myopic allocation policy is adopted instead.

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1. Introduction and problem definition

As the competition in high-tech markets becomes more and more intense, product differentiation and customization become a top priority for many companies. For instance, today, most companies in the computer manufacturing industry allow their customers to customize nearly every component of their products. While product customization is a must for strategic competition in these markets, increased levels of customization also come with their own operational-level challenges.

This paper studies such an operational challenge recently faced by a high-tech make-to-order manufacturing firm: Managing multiple flexible production lines to produce multiple product families so as to minimize the total operating cost (including the cost of managing process flexibility and the backlogged demand), over multiple production periods where the demand for the products is highly uncertain.

The firm which motivated this research is a manufacturer of electronic devices that consist of a single chassis and a set of parts assembled on it. Products are grouped into families depending on the chassis that they are built onto and each family requires a different set of parts. While this work was motivated by a firm in the electronics industry, many of the same issues studied here are also faced by make-to-order manufacturing firms in other industries.

On the demand side, customers are allowed to choose almost every part of their products. In particular, a customer order includes a selection of chassis type and a set of parts that are available for that chassis. Since the number of possible product configurations that can be formed by the customers is large, it is possible to start the final assembly of a product only after a firm customer order is received. On the supply side, customer orders are produced on multiple production lines, which may be adjusted to manufacture any set of product families prior to the start of production. The adjustments are time consuming and costly; hence it is not practical to change them once the production is started. The same set of assignments is preserved over multiple production periods, until a significant change in the demand pattern is observed. If the firm is short of capacity in one period, then excess demand is backlogged and carried over to the next period. Since the customers are placing orders for highly customized products, they are usually willing to wait for their orders. Cancelling an order, in case of a delay, is not very desirable for the customers since there is

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doi:10.1016/j.ejor.2011.07.043

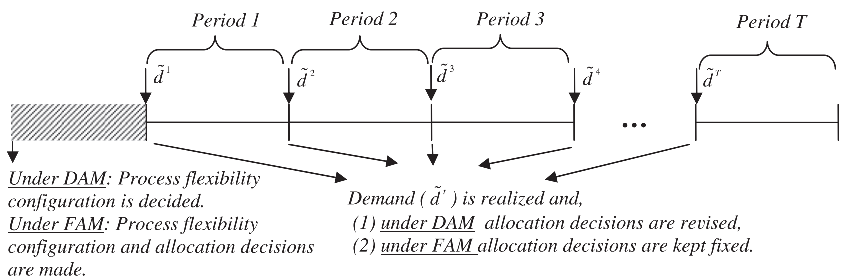

Fig. 1. A graphical representation of DAM and FAM.

no other competitor with which they can place the same order and receive it immediately.

Prior to the start of production, the firm decides a product-to-line assignment, which we refer to as the *process flexibility* of the firm. Process flexibility refers to the ability of a firm to produce multiple products on multiple production facilities or lines, as described by the process-flexibility literature (see Jordan and Graves, 1995). As greater process flexibility is adopted by the firm, i.e., as more products are assigned to more lines, the firm's ability to match capacity with demand improves. However, process flexibility comes at a cost. In particular, assigning product i to line j involves a certain cost depending on i and j due to: (1) pre-positioning the related parts and chassis inventory next to the production line, (2) computer programming and setup, which are time consuming, and (3) dedicating labor and material handling equipment to produce family i on line j during the planning horizon, which increases direct manufacturing expenses. Hence, in our model, process flexibility is a tactical level decision, which can only be revised in response to major changes in the demand pattern. The capacity investment decisions are, however, fixed in the medium- and short-term.

Once the process flexibility decision is made, operating the system by allocating capacity to demand is another practical challenge in a multi-period planning horizon. In particular, the *operational flexibility* of the firm, i.e., the ability to dynamically change capacity allocations among different product families over time, plays a critical role in the selection of capacity allocations. Further, operating decisions also affect the choice of process flexibility *ex ante*.

Regarding the operational flexibility of the firm, we consider two basic modeling approaches: (1) a Dynamic Allocation Model (DAM), where the allocation decisions are made after observing the demand at the beginning of each production period and (2) a Fixed Allocation Model (FAM), where the allocation decisions are made at the beginning of the planning horizon together with the assignment decisions and these decisions do not change in response to demand realizations from period to period.

The sequence of decisions for our firm is shown in Fig. 1. First, based on the forecasted demand, the firm commits to a process flexibility configuration prior to the start of production and incurs a certain flexibility cost. Next, at the beginning of every production period t, demand is realized and the production capacity is allocated to meet that demand, and the existing backlog, subject to the process flexibility configuration and the operational flexibility of the firm. Unmet demand from period t is backlogged. The overall objective (under both DAM and FAM) is to minimize the total operating cost over the planning horizon, which includes the cost of process flexibility and the expected cost of total backlog.

As the sequence of decisions suggests, we model DAM as a multi-stage stochastic integer program with binary decisions only in the first stage and FAM is modeled as a single stage stochastic integer program. We also provide effective procedures to solve our mathematical models. Regarding our solution methods, the solution methodology developed for FAM handles non-identical and correlated demand both across time and product families. We require demand to be independent across time when solving DAM, but it need not be identically distributed and we can handle inter-product dependencies. Assuming independence across time is reasonable for a make-to-order firm involved in mass customization facing an aggregate demand that comes from a large number of customers who act independently.

Note that FAM has no operational flexibility since each line is allocated a fixed time to produce a certain family, while DAM has full operational flexibility. Fixing allocation decisions may have significant operational benefits including: reduced scheduling problems, operational standardization and increased efficiency (Li and Tirupati, 1997). However, in our setting, quantifying these benefits is not straightforward since it is not easy to incorporate them in a mathematical decision model. In practice, our firm employs an operating policy that is close to FAM (allocations are rarely changed in response to demand). So, in this paper, FAM serves as a benchmark to evaluate the potential benefits of operational flexibility observed under DAM.

We provide two sets of computational analyses. First, we quantify the potential benefits of operational flexibility by comparing the performance of DAM and FAM. These models simultaneously optimize for process flexibility and the capacity allocation decisions. Second, we investigate the value of process flexibility in a multi-period production framework under different dynamic operating policies. For this purpose we introduce the myopic version of DAM as a third operating model (MDAM) where the firm may change the allocations at the beginning of each period, but does so without taking the impact on future periods into account. By comparing the value of process flexibility under DAM and MDAM, we show that process flexibility may not only be used to hedge against the demand uncertainty, but may also be employed to protect against possible suboptimal operating decisions in the future.

The rest of the paper is configured as follows: In Section 2, we provide a brief review of the related literature and outline our contributions. In Section 3, FAM is explained in detail and an effective solution algorithm is presented. Section 4 explains the DAM and presents a sampling-based decomposition method to find a near-optimal solution. Section 5.1 presents a computational study of the benefits of operational flexibility by comparing the performance of FAM and DAM. Section 5.2 is dedicated to the analysis of the value of process flexibility and operating policies. We conclude with a brief discussion of results and future research directions in Section 6.

2. Literature review

Our paper is most closely related to the capacity-flexibility literature. The literature on capacity flexibility is extensive, but the related literature can be categorized in two main streams. The first stream focuses on investment in resources that are dedicated *versus* totally flexible. The second stream explores process flexibility, i.e., the ability of a firm to produce multiple products on multiple production facilities or lines. The former stream includes Fine and Freund (1990), Van Mieghem (1998), Li and Tirupati (1994, 1995, 1997) and Van Mieghem and Rudi (2002).

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