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Process flexibility and the chaining principle in lot sizing problems

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ABSTRACT

We analyse the value of process flexibility in the context of a short-term deterministic lot sizing problem with backlogging, where several types of products can be made on several alternative resources. It may be very costly in practice to install resources that have complete flexibility. Therefore, it might be interesting to only implement a limited amount of flexibility so that each resource can produce only certain types of items. The flexibility decision is taken at the start of the horizon. In order to study the value of such process flexibility, we perform several analyses. First, for a standard formulation we analyse the benefits of a long chain configuration and compare this to several other configurations (such as the case with no flexibility, clustered flexibility and complete flexibility). To further analyse the benefits of the long chain, we propose a new model to determine the best long chain (given that many alternative long chain configurations exist with a different total cost). Second, we propose a new optimization model that considers the possibility of investing in flexibility and determines the best flexibility configuration for a given budget. Our computational results show that almost all benefits of process flexibility are found by adding a limited number of links, but not necessarily according to the chain principle. Further analyses also indicate that backlog cost heterogeneity, demand heterogeneity and the presence of setup times have a large impact on the value of flexibility.

1. Introduction

In this paper, we analyse the concept of process flexibility in the context of a deterministic production planning problem. The concept of process flexibility in a supply chain relates to the type of products that can be manufactured on various alternative resources such as plants or machines. Since total process flexibility can be very expensive, it is very important to study ways to implement a limited amount of flexibility to balance the costs and the benefits. Jordan and Graves (1995) analysed the value of manufacturing process flexibility in a stochastic model with a single period and single stage production environment where multiple products can be produced in different plants with limited capacity. The main insight from the paper is that almost all of the benefits of total flexibility can be achieved by implementing only a small amount of flexibility, but in a smart way using the chaining concept. A “chain” is a group of products and plants which are all connected, directly or indirectly, by product assignment decisions. Within a chain, a path can be traced from any product or plant to any other product or plant via the product assignment links. The key idea behind chaining is that excess capacity can be shifted - to some extend - along the chain and hence decrease the amount of lost sales.

Although the value of process flexibility as a strategic decision is typically analysed in a context with stochastic demand, this study shows that process flexibility can already have a significant value in a short-term deterministic planning environment. In such a context, the flexibility configuration decision becomes an operational decision which is taken at the start of the horizon when the demand for the planning horizon is known. The flexibility configuration remains then fixed for the current planning horizon. This is hence a fundamentally different situation compared to the stochastic setting in which the flexibility decisions must be taken without knowing the exact demand. Such a situation happens for example in the semiconductor industry where machines must be qualified before being able to produce certain products, and these qualification decisions are periodically reevaluated (Johnzén et al., 2011; Rowshannahad et al., 2015). This qualification process hence constitutes the decision on the flexibility configuration. However, qualifying a machine for a specific product can be a very costly task and is hence only done periodically (Rowshannahad et al., 2015). Ignizio (2009) presents an integer programming optimization model in order to determine the best qualification configuration in a

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semiconductor plant. This decision is made at the beginning of the week, given the information on the different jobs that need to be processed during the week. At the moment of the qualification decision, the demand over the planning horizon is hence known. Aubry et al. (2008) present a mixed integer programming optimization model to determine the best qualification in a more general multi-machine workshop for a given demand.

Our main research objective is to study the impact of the flexibility configuration in a deterministic context. We consider the case of multi-period production planning where demand is known in advance, but varies over time. The mathematical optimization models used for these situations are known as deterministic lot sizing models. The basic lot sizing problem consists of determining the size of production lots, i.e., the amounts of each product to be produced in each of the periods in the planning horizon, in a way that minimizes total costs, respects the resource availability and meets the known demand of the products (Pochet and Wolsey, 2006). In case demand cannot be satisfied on time, it will be backlogged. Such a situation typically arises when not enough capacity is available. This has similarities to the lost demand in the stochastic single period problems. However, since we consider a multi-period planning horizon, we have the opportunity to still satisfy that demand, but at a later date. Backlogging decreases the customer service level and hence it is penalized in the objective function. The flexibility decision will have an impact on the backlog level in the deterministic case, just as it will have an effect on the amount of lost sales in the stochastic setting.

This paper has the following contributions. First, we analyse the effect of long chains, such as proposed in Jordan and Graves (1995), in a lot sizing problem with backlog and compare this against several other configurations. In some sense it extends the chaining principle for a multi-period setting and we show that flexibility also has value in a deterministic setting. Second, we show how different parameters such as the number of resources and products, the backlog cost, the demand distribution and the setup times have an impact on the value of flexibility. Third, we propose a new model to find the best long chain configuration among all possible long chain configurations. The formulation is flexible and can be used to find the best assignment if an arbitrary structure is imposed. Fourth, we propose a new optimization model which optimizes the flexibility configuration subject to an additional global budget. Such a model enables us to check the structure of the optimal configuration within a limited budget for various levels of input parameters. Finally, computational experiments are performed to show the effect of the flexibility configuration on the total cost. Our computational results show that the benefits of the best long chain are very close to the ones obtained by the total flexibility configuration for high levels of capacity and for homogeneous cost and demand scenarios. However, for low capacity levels and for non-homogeneous cost and demand scenarios, the best long chain has a substantial performance difference compared to the total flexibility case. Moreover, we observe that almost all benefits of process flexibility are found by adding a limited number of links, but not necessarily according to the chain principle.

The paper is organized as follows. In Section 2, we present a brief literature review on the multi-machine lot sizing, process flexibility and the chaining principle illustrating the main insights that have been proposed for stochastic manufacturing systems. In Section 3, we provide the mathematical models for the lot sizing problem with machine flexibility. Section 4 presents the analysis of process flexibility and shows the computational results considering various flexibility configurations in a homogeneous setting. In Section 5, we present a sensitivity analysis of the computational results proposing different scenarios. Finally in Section 6, we present our conclusions.

2. Literature review

Although process flexibility and the chaining principle have not been addressed in the context of deterministic lot sizing problems, these concepts have been studied by several researchers considering a stochastic point of view. In the first subsection we review lot sizing studies that are related to our problem while in the second subsection we discuss the main insights derived in the literature related to process flexibility and chaining.

2.1. Multi-machine lot sizing

The class of lot sizing problems which are relevant for this research are the lot sizing problems with multiple parallel resources. This problem appears in several industrial applications, such as tile production (de Matta and Guignard, 1994), pharmaceutical production (de Matta and Guignard, 1995), packing for yogurt production (Marinelli et al., 2007), the tire industry (Jans and Degraeve, 2004) and the textile industry (Silva and Magalhaes, 2006).

There are many studies in the literature on the lot sizing problem with parallel machines considering complete machine flexibility. For the problem with identical machines, Lasdon and Terjung (1971) propose a heuristic for a lot sizing and scheduling problem without setup time. Carreno (1990) also proposes a heuristic for this problem with setup time and constant demand. Jans (2009) proposes new constraints to break the symmetry that is present due to the identical machines. For the unrelated parallel machines case, Toledo and Armentano (2006) relax the capacity constraints and propose a Lagrangian heuristic. Fiorotto and de Araujo (2014) use a network reformulation of the problem and instead of the capacity constraints, they relax the demand constraints using Lagrangian relaxation and also propose a heuristic to find feasible solutions. Fiorotto et al. (2015) present hybrid methods using Lagrangian relaxation and Dantzig-Wolfe decomposition and find better lower and upper bounds compared to Toledo and Armentano (2006) and Fiorotto and de Araujo (2014).

Although the lot sizing problem on parallel machines with a limited amount of flexibility is a natural and more realistic extension of the standard assumption, only very limited research has been done on this topic. In their application in the tire industry, Jans and Degraeve (2004) discuss a problem where not all types of tires can be produced on all types of heaters. Xiao et al. (2015) propose a hybrid Lagrangian and simulated annealing based heuristic for the capacitated parallel machine lot sizing and scheduling problem where not all machines are eligible to produce all items. Our paper adds to this literature on lot-sizing problems on parallel machines with limited flexibility by considering the flexibility configuration as a decision variable.

2.2. Process flexibility and chaining

The seminal paper of Jordan and Graves (1995) is the first to consider the design and effectiveness of a limited amount of process flexibility. Analysing a manufacturing system with stochastic demand, they show that a chained configuration of products and plants (see Fig. 1) performs almost as well as the total flexibility configuration in terms of average sales and capacity utilization. Among all partial flexibility configurations, the chaining concept is still one of the most influential strategies studied in the literature on manufacturing systems and used in practice, in particular, in the automotive industry (Graves and Tomlin, 2003).

Sheikhzadeh et al. (1998) present analytical models for the performance evaluation of both chained and total flexibility configurations in which the stochasticity studied is related to the arrival process and processing times. The configurations are compared under different sets of loading conditions, varying buffer sizes and number of items and machines. They conclude that a single long chain configuration is always superior to multiple smaller chains. However, the incremental benefit of a single long chain is shown to decrease with the length of the chain. Considering an uncertain demand, Graves and Tomlin (2003) extend the work of Jordan and Graves (1995) to multistage supply chains and develop insights into strategies for the deployment of