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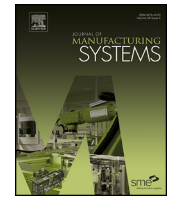

Technical Paper

The impact of lot-sizing in multiple product environments with congestion

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ABSTRACT

We present a production planning model for a multiple product single machine dynamic lot-sizing problem with congestion. Using queuing models, we develop a set of functions to capture the nonlinear relationship between the output, lot sizes and available work in process inventory levels of all products in the system. We then embed these functions in a nonlinear optimization model with continuous variables, and construct an approximate solution to the original problem by rounding the resulting fractional solution. Computational experiments show that our model with congestion provides significantly better flow time and inventory performance than a benchmark model that does not consider the effects of congestion. These advantages arise from the use of multiple smaller lots in a period instead of a single large lot as suggested by conventional fixed-charge models without congestion.

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1. Introduction

Lot sizing problems constitute an important class of production planning models that arise when production equipment requires significant setup times to switch from the processing of one product to another [1]. The key decision variable is the lot size, the quantity of a specific product that is issued as a job to the production process. In a production setting, a large lot size yields high resource utilization due to fewer setups between products, but can result in increased finished goods inventory. Processing a large lot of one product may also delay the production of other lots, creating variability in the flow of products through the system [2]. A small lot size has advantages in processing individual orders in a timely manner and minimizing work-in-process (WIP) inventory and cycle times. However, frequent setups can consume excessive amounts of capacity, leading to long cycle times in the system [2]. Clearly, wherever possible, setup times should be reduced or eliminated, but there remain areas where this cannot be accomplished economically.

Most deterministic lot sizing models focus on the tradeoff between the fixed cost of setup that is independent of the lot size, and the holding cost of the cycle stocks due to production occurring in batches. This approach is easily defensible in a purchasing context, where the fixed cost represents the costs of placing the order and delivering the material. However, in a production context the problem is more complex. The primary difficulty centers on obtaining realistic estimates of the setup costs, particularly under time-varying resource utilization. In many industrial environments, the direct incremental cost of setup activity is often limited to the amount of scrap produced while adjusting tooling; labor and machine time costs are fixed in the time frame relevant to the lot sizing decision [3]. Hence much of the setup cost can be viewed as the opportunity cost of the capacity foregone in the setup time, which will vary over time depending on, among other things, the utilization level of the resource in question at that point in time. However, since this cost will vary over the planning horizon in the face of dynamic demands, it is difficult to estimate in practice. Hence a lot sizing model that can incorporate the effects of setups on the dynamics of the production system directly, without the need for cost parameters that are difficult to estimate, is very desirable.

The work in this paper differs from most previous lot sizing models in its explicit representation of throughput as a function of average WIP, number of lots and lot size. Setup cost is not explicitly considered since the costs of setup decisions are directly captured in the performance measures of the system. Our model can easily be modified to account for incremental, direct costs of setups, such as those arising from scrap, if necessary. We envision this model

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being used in tactical decision making, where a firm may want to update its lot sizes in the face of changing demands and product mixes over time. Frequent changes in manufacturing lot sizes at very short intervals are clearly difficult to implement in practice, and hence are not considered.

In this paper we present an exploratory analysis of these issues in the context of a multi-product single machine dynamic lot sizing problem. We first develop a set of nonlinear functions to capture the interactions between lot sizes, throughput, cycle time, and WIP, following the development of Karmarkar [4,5]. We then present a nonlinear integer programming formulation for a multi-product, single machine, deterministic dynamic lot sizing problem with the objective of minimizing the total costs of WIP, finished goods inventory (FGI) with backlogging. Since this model is computationally intractable even for small instances, an approximate solution is constructed by applying a simple myopic rounding scheme to the solution obtained from a continuous relaxation. While this approach can, of course, make no claims of optimality, it permits computational experiments comparing the solutions thus obtained to those from exact integer programming models that do not consider congestion.

We find that our model provides lower cycle times and WIP levels than an alternative model that does not consider congestion. In addition, discrepancies between planned and realized performance are considerably smaller in our model, despite the extremely simple approximation approach used. These findings suggest that even with the very simple approximate solution procedure we use, the explicit consideration of congestion in lot sizing problems can be beneficial.

The next section presents a brief review of previous related work. Section 3 introduces the functions used to represent the nonlinear relation between queue size and lead times of products. Section 4 incorporates the functions developed in Section 3 into a multi-product dynamic lot sizing model. Section 5 introduces the conventional lot sizing model without congestion that is used as a benchmark in our experiments. Section 6 presents the computational experiments comparing the performance of the models. We conclude the paper with a summary of the main conclusions and highlight some possible directions for future work.

2. Previous related work

The literature on modeling production systems can be classified into two main categories. The first of these is stochastic performance analysis models, which characterize system performance measures based on a probabilistic model of the system. Within this area, queuing models have been shown to capture important aspects of system behavior [2,6]. A fundamental insight from queuing models is that system performance measures, especially cycle times, degrade nonlinearly as utilization increases. In addition, degradation of system performance begins to occur well before the system approaches 100% utilization. Karmarkar and his coworkers [5,8–10] provide an excellent discussion of the relationships between lot sizes, lead times and WIP, which forms the basis for the work in this paper. In particular, Karmarkar et al. [45] develop an optimization model based on the queuing relationships derived by Karmarkar [8], and suggest a number of heuristics for its solution. Zipkin [11] examines a queueing-inventory system consisting where an inventory facing stochastic demand is replenished from a production facility represented as a queue. Benjaafar [12] extends these queueing models to examine the effect of transfer batches on cycle times, while Benjaafar and Sheikhzadeh [13] study the interactions between scheduling policies and lot sizing decisions. In a similar spirit to our work, Vaughan [14] proposes a joint queueing – reorder point model that examines the effect of shortage cost on the optimal lot size. The model he proposes represents the long-run steady-state behavior of the system, and does not allow the integrated planning of release quantities and lot sizes over time, which is the aim of the model presented here.

The other stream of literature involves a number of deterministic techniques [15–18] whose objective is to allocate resources to products over time under estimated demands while optimizing system performance. The basic approach is to divide the planning horizon into discrete time periods, and allocate the capacity in each period to products in a manner satisfying a set of aggregate constraints that represent system capacity and dynamics. However, a solution satisfying the aggregate constraints may turn out to be impossible to execute since the operational dynamics, especially cycle times, are not modeled explicitly.

Deterministic lot sizing models form an important portion of this second class, and have been studied extensively since the seminal work on the classical economic order quantity (EOQ) model [19]. Most lot-sizing models consider the trade-off between setup cost and finished goods inventory holding cost, resulting in a fixed-charge problem structure that introduces substantial economies of scale into the problem. Hence models of this form tend to propose solutions where demand for several time periods is batched to amortize the fixed setup costs over a larger number of units. Exact solutions have been obtained using dynamic programming and mixed-integer programming. The dynamic programming approaches date back to the work of Wagner and Whitin [20], and must exploit specific problem structure to obtain polynomial-time solutions. Wagner and Whitin [20] propose a dynamic programming algorithm for the uncapacitated problem with setup costs, production and inventory holding costs without backlogging. The single-product problem with capacity constraints is shown to be NP-complete under quite mild conditions by Florian et al. [21]. Florian and Klein [22] extend the dynamic programming approach to the case with capacity constraints, while Zangwill [23,24] develops the network flow aspects of the problem. Later work on dynamic programming models has focused on reducing their computational time by exploiting problem structure [25–27], relaxing the assumptions of the problem [28], and exploring the optimality of the dynamic programming algorithms, most notably the Wagner–Whitin algorithm, in the rolling horizon context [29–32].

Multi-item dynamic lot sizing problems have generated considerable interest due to their close links with the widely used material requirements planning (MRP) approach [33]. These problems have generally been formulated as mixed integer programs. Early work focused on branch and bound algorithms using lower bounds derived from Lagrangian relaxation [34–38]. The closely related methods of column generation have also been used [39,40]. The polyhedral structure of these integer programs has been the subject of considerable research [41]. Erenguc and Mercan [42] present a multi-item lot sizing problem in which setup times for both individual items and family setups are included. There are also a wide range of heuristics for both single and multi-item problems (e.g., [43,44]).

In summary, despite the extensive body of work, however, the relationship between WIP, utilization and cycle times has generally not been considered in capacitated lot sizing models [7]. The work in this paper is the first to our knowledge that incorporates the nonlinear relations between WIP, lot sizes and utilization into a dynamic lot-sizing model for multiple items.

3. Output functions for a multi-item production system with setup times

The *M*/*G*/*1* queuing model, which has been shown to be effective in modeling production systems [46] is used to model congestion

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