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Technical Paper

Effect of setup time reduction on supply chain safety stocks

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ABSTRACT

In most safety stock placement models, manufacturing lead times are treated as constant and exogenous quantities. In reality, however, manufacturing lead times depend on operating policies such as batch sizing and can be decreased by systematic investments in setup time reduction. This paper considers a manufacturer supplying a distribution network and integrates strategic safety stock placement with setup time reduction and batch sizing. We formulate the integrated problem with the objective of minimizing work-in-process and inventory holding costs and setup time reduction investment. An existing dynamic programming algorithm is extended to solve this problem efficiently. Using a two-stage distribution network, we characterize analytically the impact of setup time, batch sizes and integration on optimal positioning of safety stocks. Numerical studies on a three-stage network highlight the economic value of integration and setup time reduction. Setup time reduction is shown to be highly effective when utilization is high or when it can be accomplished with small investments. The savings from integration are high when value added at the manufacturer is high, and low when the marginal cost of setup reduction is either very high or very low.

1. Introduction

In recent years, global competition and evolving customer expectations of shorter lead times and higher service levels have brought manufacturing supply chains under an unprecedented pressure to sustain competitive advantage. Inventory optimization, reducing operating costs and increasing service levels are now top priorities among supply chain managers across industries [1,29]. However, the effectiveness with which these goals are achieved depends largely on cooperation and coordination at various decision-making levels [4,9,7]. In this paper, we integrate safety stock placement in a distribution network with setup time reduction and batch sizing at a manufacturer.

Safety stock placement involves the determination of optimal locations and quantities of safety stocks in a network needed to meet target service levels [14]. These models often treat the lead times at manufacturing stages as *given*, and neglect the impact of manufacturer's operating policies on safety stock placement. Kumar and Aouam [25] relaxed this assumption by modeling lead times as functions of batch sizes. They showed that the integration of these decisions could generate significant savings in total operating costs. Their study, however, considered the setup time required by each batch as a constant. In many manufacturing settings, setup times can be reduced by making investments in revising setup procedures, modifying tools and fixtures, or introducing robotic equipments, etc. [30]. Shorter setup time results in reduced manufacturing lead times and smaller batch sizes and directly impacts safety stock costs [33,34]. Existing models of setup time reduction mainly focus on its impact at a single stage (or at the manufacturer) [38,30], while its impact on safety stocks and their placement is largely neglected. The current paper extends the works of Nye et al. [30] and Kumar and Aouam [25] to jointly optimize setup time, batch sizes and safety stock placement in a distribution network.

We consider a distribution network (DN) that procures finished goods from a single manufacturer. All stages in the DN are potential locations for holding safety stocks. External demand occurs at end-stages and lead time demand is assumed to be normally distributed. Distribution stages follow a periodic-review base-stock policy with a common review period among all stages. The network operates under the guaranteed service approach (GSA) [36], such that each stage guarantees a deterministic service time within which 100% of all orders are fulfilled. As in other GSA models, stages maintain a base-stock level to meet a target service-level of the orders from stock, while the remaining quantity is assumed to be expedited using special measures [13]. Further, we assume that the manufacturer can be modeled as a $G/G/1$ queuing system that requires setup between batches. The setup time can be reduced by making an investment [3]. Lead time at the manufacturer is modeled as a deterministic delay that includes mean

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production cycle time and a safety time to cover production cycle time variance, both of which are functions of setup time and batch size.

Our analysis focuses on assessing the value of jointly optimizing setup time and batch sizes with safety stock placement. We first analyze a simple network with a manufacturer supplying a two-stage system with one warehouse and one retailer. We study the impact of setup time and batch size on the optimal placement of safety stocks at the warehouse and retailer. Results indicate that a reduction in setup time tends to push all safety stocks downstream (retailer); while a batch size that is too small or too large results in decoupled safety stocks at both the warehouse and retailer. We also note that the integrated problem has a greater tendency of coupling safety stocks at the retailer than a sequential approach. Second, we extend an existing dynamic programming algorithm of Graves and Willems [13] to solve the integrated problem for distribution networks with several warehouses and retailers. Numerical studies on a three-echelon network suggest that the integrated problem results in shorter setup time, smaller batch sizes and reduced inventory. Lastly, we demonstrate the economic benefits of integration and setup time reduction. We show that the marginal benefits of setup time reduction increase with utilization and decrease with the required investments. The value of integration is high when the value added at the manufacturer is high, and is low when the cost of reducing setup is either very high or very low.

The paper is structured as follows. Section 2 discusses the previous related work. Section 3 defines the assumptions and notation, and formulates the integrated problem. In Section 4, we analyze the impact of setup time and batch size on safety stock placement in a simple network consisting of a manufacturer and two distribution nodes. Section 5 describes a dynamic programming algorithm to solve the integrated problem, and Section 6 presents multistage numerical experiments and insights. We conclude in Section 7 with a discussion of directions for future research.

2. Previous related work

Our work lies at the intersection of two distinct fields of literature: the guaranteed-service approach (GSA) for safety stock placement and queuing models for setup time reduction and batch sizing.

The GSA addresses the strategic placement of safety stocks in multi-echelon networks. Under this approach, each stage in the network quotes to its customers a guaranteed service time within which it is able to meet a bounded demand from stock. The demand exceeding the demand bound is handled through special measures such as overtime or subcontracting. These assumptions of guaranteed service times and bounded demand were first proposed in Simpson [36], a study that forms the cornerstone of this stream of research. The author studied the case of serial networks operating under a periodic base-stock policy and showed that at optimality a stage either holds safety stocks for its entire incoming lead time or nothing at all. Graves and Willems [13] formalized this framework and extended it to the case of spanning-tree networks. Since then, these models have enjoyed great success in both research and industry with successful applications at Eastman-Kodak [13], Hewlett-Packard [5], and Intel [41], to name a few. Eruguz et al. [10] give a comprehensive review of recent advances in the GSA.

A key assumption underlying most GSA models is that of exogenous, fixed lead times. However, in many manufacturing environments, lead times are a result of various tactical and operational decisions taken at the production level [20]. Graves and Willems [15] proposed a GSA model that treated lead times as decision variables to be chosen from a set of available options. They developed a framework to determine the optimal configuration of a supply chain, including suppliers, manufacturing technologies and shipment options. An option in their model could denote implementing a tactic that leads to a reduction in lead times; however, the relationship between lead times and capacity was not modeled explicitly.

Lemmens et al. [28] and Kumar and Aouam [25] used queuing models to capture the impact of capacity and congestion effects on lead times. Both these models considered manufacturing environments that involve setup and require items to be produced in batches. Lemmens et al. [28] modeled production stages as $G/G/m$ queuing systems and expressed the mean and variance of production cycle times as functions of batch sizes using results from Lambrecht and Vandaele [27]. The batch sizes were assumed to be exogenous and were not optimized in this study. Kumar and Aouam [25] considered a network of production facilities where each facility was modeled as a $G/G/1$ system. They modeled lead times as a sum of mean production cycle time, which is a function of batch size, and a constant safety time to cover the variability. They optimized batch sizes to minimize the sum of setup cost, WIP holding cost and safety stock costs in the network. For a fixed setup time, they demonstrated the economic value of jointly optimizing batch sizes and lead times with safety stocks.

In a related study, Vaughan [39] studied the impact of batch sizes on the lead time demand distribution for a manufacturer-warehouse system operating under the stochastic service approach (SSA) and a (Q, r) ordering policy. The author showed that the consideration of safety stock holding costs and shortage penalties lead to optimal batch sizes that are larger than those obtained by minimizing only the WIP and cycle stock holding costs. The author also suggested setup time reduction as a measure to reduce batch sizes and total costs, however, this was not studied analytically.

In both research and practice, the reduction of setup time is widely recognized as an effective tactic to manage and reduce lead times [34,16,35,33,11,12]. Shorter setup times are linked to smaller batch sizes, reduced inventory, improved quality, increased flexibility and greater responsiveness [2]. Kannan and Tan [18] found that improved material flow through setup time reduction and shorter batch sizes positively affects business performance. It is for these reasons that manufacturing philosophies such as continuous improvement (Kaizen) and just-in-time (JIT) lay great emphasis on setup time reduction. Shingo [35] advocated the use of tools such as single-minute exchange of dies (SMED) and urged organizations to strive for setup times below 10 min. These practices, however, are qualitative in nature and do not provide economic justifications for the investment needed against the benefits derived, neither do they rationalize the arbitrary target of 10 min [30]. For this purpose, Trevino et al. [38] proposed a mathematical model to evaluate the optimal setup time reduction to balance a sum of inventory cost, setup cost, storage cost and quality cost against the setup time reduction cost. They demonstrated that an unbounded reduction in setup times is not justified, and batch sizes must be reduced appropriately to increase the benefits of setup time reduction.

Yang and Deane [42] modeled an $M/G/1$ queuing system and showed that setup time reduction leads to reduced mean and variance of production cycle time, and that marginal improvement in performance from setup reduction decreases as setup time gets lower. They also provide suggestions for allocating limited capital for setup reduction among a heterogeneous mix of products. Nye et al. [30] also considered an $M/G/1$ queuing system and proposed an analytical model to determine the optimal setup time and batch size while considering their impact on work in-process inventories. They considered a linear investment function, and showed that the optimal setup time exists at extreme points i.e. either no reduction or enough reduction to achieve a batch size of a single unit. However, a strictly convex investment function could lead to intermediate values of setup reduction. Other studies such as Spence and Porteus [37], Kim et al. [21], and Kreng and Wu [24] consider setup time reduction in the context of economic order/production quantity (EOQ/EPQ) models.

While it is widely recognized that reductions in setup time reduce safety stocks by reducing the mean and variance of production cycle times, their impact on safety stock placement in supply chains has not yet been studied. The current study is a direct extension of Kumar and Aouam [25] and Nye et al. [30], where we jointly optimize setup times, batch sizes and safety stocks. The paper provides clear insights on the