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Integrated safety stock management for multi-stage supply chains under production capacity constraints

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ABSTRACT

In the petrochemical, chemical and pharmaceutical industries, supply chains typically consist of multiple stages of production facilities, warehouse/distribution centers, logistical subnetworks and end customers. Supply chain performance in the face of various market and technical uncertainties is usually measured by service level, that is, the expected fraction of demand that the supply chain can satisfy within a predefined allowable delivery time window. Safety stock is introduced into supply chains as an important hedge against uncertainty in order to provide customers with the promised service level. Although a higher safety stock level guarantees a higher service level, it does increase the supply chain operating cost and thus these levels must be suitably optimized.

The complexities in safety stock management for multi-stage supply chain with multiple products and production capacity constraints arise from: (1) the nonlinear performance functions that relate the service level, expected inventory with safety stock control variables at each site; (2) the interdependence of the performances of different sites; and (3) finally the margin by which production capacity exceeds the uncertain demand. Given the complexities, the integrated management of safety stocks across the supply chain imposes significant computational challenges. In this research, we propose an approach in which the evaluation of the performance functions and the decision on safety stock related variables are decomposed into two separate computational frameworks. For evaluating the performance functions, off-line computation using a discrete event simulation model is proposed. A linear programming based safety stock management model is developed, in which the safety stock control variables (the target inventory levels used in production planning and scheduling models, base-stock levels for the base-stock policy at the warehouses) and service levels at both plant stage and warehouse stages are used as important decision variables. In the linear programming model, the nonlinear performance functions, interdependence of the performances, and the safety production capacity limits in safety stock management are properly represented.

To demonstrate the effectiveness of the proposed safety stock management model, a case study of a realistically scaled polymer supply chain problem is presented. In the case problem, the supply chain is composed of two geographically separated production sites and 3–8 warehouses supplying 10 final products to 30 sales regions.

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1. Introduction

In the petrochemical, chemical and pharmaceutical industries, supply chains typically consist of multiple stages of production facilities, warehouse/distribution centers, logistical subnetworks and end customers. When events, such as changes in the characteristics of the uncertainties, shifts in the demand to capacity ratio, introduction of a new product and retirement of a matured product, or entrance of new competitors take place, the optimal safety stock level at each stage of the supply chain needs to be re-evaluated. Thus, cost effective and agile safety stock management represents a competitive advantage for a company in a dynamic and highly competitive market.

Supply chain performance in the face of various market and technical uncertainties is usually measured by service level, that is, the expected fraction of demand that the supply chain can satisfy within a predefined allowable delivery time window. Safety stock is introduced into supply chains as an important hedge against

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uncertainty in order to provide the customer with promised service level. Although a higher safety stock level guarantees a higher service level, it does increase the supply chain operating cost and thus these levels must be suitably optimized.

The chemical process industry has a history of using deterministic linear programs (LP) and/or mixed integer linear programs (MILP) for production planning and scheduling. In such production planning and scheduling formulations, the notion of safety stock is imbedded by including lower bounds on the inventory levels of various products and/or production sites (Jung, Blau, Pekny, Reklaitis, & Eversdyk, 2004; McDonald & Karimi, 1997). This lower bound is usually referred to as "target inventory level." The safety stock level is usually defined as the average inventory level measured at a minimum inventory recording time interval. Since the length of periods during which the target inventory constraints are enforced in the planning or scheduling models may be different from the minimum inventory recording time interval, the target inventory level and measured safety stock level usually take different values. Thus, in a production systems using such planning and scheduling models, the target inventory level is the only control variable of the safety stock levels.

On the other hand, across diverse sectors of the industry, the base-stock policy (or order-up-to policy) is widely employed for management of pure inventory systems such as warehouses and distribution centers. The base-stock level (or order-up-to level) is the target level of the inventory position that should be constantly maintained. The inventory position is the sum of the amount of orders placed but yet to be delivered and the net inventory level at the site. Thus, the safety stock level for the pure inventory system is controlled by the base-stock levels.

Each production or warehouse site in the supply chain exhibits its unique performance functions that relate the service level and the safety stock level to the safety stock control variable of the target inventory or the base-stock level. Evaluating this function for individual products at each site is one of the important issues to be addressed in this research. The estimation of the performance functions for pure inventory systems has attracted a large body of research. Due to their relative simplicity, one can employ simple discrete event simulation-based models for such systems. However, the performance functions of production-inventory systems are dependent on the production planning and scheduling decisions. Therefore, we propose a Sim-Opt based approach to estimate the performance functions of the latter types of production systems.

Given the performance functions, it is relatively straightforward to determine the safety stock control variables of individual sites. However, the interdependence of the performance of the upstream supplier and downstream customer site necessitates decision-making with an integrated view of the multi-stage supply chain. Since the performance functions are nonlinear in nature, the integrated management of safety stocks across the supply chain imposes significant computational challenges.

In this paper, we discuss the characteristics of and methodology for estimating the nonlinear performance functions, the interdependence between the service levels at different stages and the safety capacity ensuring the sustainability of safety stock level at manufacturing sites along with the methodologies of capturing this system specific characteristic. Finally, we propose a linear programming model that solves the problems of optimal placement of the safety stocks in a multi-stage supply chain. The model incorporates the nonlinear performance functions, the interdependence between the service level at different stages of supply chain and the capacity constraint.

To demonstrate the performance of the computational framework, a case study with a realistically scaled polymer supply chain problem is presented. In the case problem, the supply chain is composed of two geographically separated production sites and 3–8 warehouses supplying 10 final products to 30 sales regions.

2. Review of literature

Since the 1950s, there has been a large body of research in the area known as stochastic inventory theory. The classical EOQ (economic order quantity) model, Newsvendor model, and the optimal ordering policies, such as (S,s), (Q,r) and the base-stock policy, form the classical work in the area and are devoted to the determination of optimal ordering quantities at a single inventory location. An extensive discussion of this classical work can be found in Porteus (2002) and Hopp and Spearman (2000).

Based on this classical work, research in inventory theory has been ongoing to extend these analytical results to conditions experienced in the day-to-day operation and design of supply chains. The works of Clark and Scarf (1960) and Schmidt and Nahmias (1985) usually serve as starting points for research that extends the fundamental single inventory location problem to multi-stage supply chain optimization problems. For a comprehensive review of this work, readers are referred to Graves (1988) and Lee and Billington (1993). Among the extensive literature in the area, the works of Lee and Billington (1993), Glasserman and Tayur (1995), Ettl, Feigin, Lin, and Yao (2000) and Graves and Willems (2000) are most closely related in intent to our research, namely safety stock management in multi-stage supply chains under production capacity limits. Lee and Billington (1993) propose a decentralized supply chain model for the determination of the base-stock level that ensures target service level or the service level that is achievable at a given base-stock level. Their analytical framework takes into account the impact of upstream service level on the downstream service level by modeling the expected replenishment lead time at each inventory location as a linear function of the service level and expected delay time of supplying upstream. Glasserman and Tayur (1995) developed simulation-based methods (IPA: Infinitesimal Perturbation Analysis) for estimating sensitivities of inventory costs with respect to policy parameters (base-stock levels) in multi-stage capacitated production-inventory systems. The work of Ettl et al. (2000) is similar to that of Lee and Billington (1993) in that both models pay close attention to interdependence of base-stock levels at different inventory sites and how this interdependence affects system performance. Graves and Willems (2000) modeled the multi-stage supply chain problem as a deterministic nonlinear optimization problem and proposed a dynamic programming algorithm to solve the problem.

It is notable that in the above mentioned references the inventory system is generalized to include the production function by incorporating the production lead times in the inventory replenishment lead times and, thus, providing a framework for characterizing the generalized inventory system that employs the base-stock policy. However, we find that the base-stock policy based analytical framework is insufficient for the analysis of the more complex production systems that arise in the chemical process industry. Specifically, the base-stock policy cannot provide adequate guidance on the allocation of resources to products in competitive situations such as occur when multiple products share a production unit. In such cases, it is necessary to utilize optimization models for the production planning and/or scheduling that guides the capacity allocation, sequence and amount of production in an adaptive mode.

An advantage of simulation-based methods, as mentioned in Glasserman and Tayur (1995), is the comparative ease with which they incorporate complicated features of real systems that mathematical modeling based methods fail to capture. Subramanian, Pekny, and Reklaitis (2000) proposed a simulation-based opti-

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