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Optimal multi-stage logistic and inventory policies with production bottleneck in a serial supply chain

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ABSTRACT

Bottleneck appears in a serial supply chain if the minimum production rate at all stages is smaller than the demand rate. Operation manager must focus on keeping the bottleneck stage fully utilized and forcing the other stages to produce in synch with the bottleneck. This study applies the lot size division method, the recursive tightening method, and the drum-buffer-rope strategy. A pull and reverse pull algorithm is designed to solve the multi-stage logistic and inventory problem with a production bottleneck in a serial supply chain. A numerical example is included to illustrate the algorithm procedures.

1. Introduction

In the 1980s, manufacturing organizations were required to become more flexible and responsive, which involved modifying existing products and processes. Organizations even had to develop new products to meet ever-changing customer needs. In the 1990s, managers realized that material and service inputs from suppliers significantly impacted organization performances in meeting customer needs (Handfield and Nichols, 1999). Recently, continuing advances in web communications and transportation technologies have accelerated the evolution of supply chains and the techniques for managing them. Companies are recognizing the importance of incorporating supply chain strategy into their overall planning (Lummus et al., 1998).

Firms generally hold excess production capacity. This strategy allows them to respond sufficiently quickly to unexpected increases in demand, and also enables rapid delivery to the customers without overtime costs or production disruptions (Martinich, 1997). However, bottlenecks may occur in the supply chain if the minimal production rate of all stages is below the demand rate. External factors that affect the demand for firm products are sometimes beyond the control of management. A booming economy may increase demand (Krajewski and Ritzman, 1996). For example, in 1990 and 1993, Compaq Computer introduced new computer models for which demand outstripped production capacity (Burrows, 1994). On the other hand, equipment breakdowns and defects caused by machine wear are two major sources of lost production. For instance, an earthquake seriously damaged power systems and production facilities in Taiwan on September 21, 1999. The production capacities of many industries declined after the earthquake, especially those in the semiconductor industry. When production lags demand, enterprises may expand production capacity to prevent lost sales and simultaneously may markup prices to maximize profit. However, enterprises generally overlook reducing production costs, particularly logistic and inventory costs.

In typical models for determining the economic production quantity (EPQ), the supplier produces and transports a single lot product to the customer. However, in order to decrease inventory level, partial lots (batches) can be transported to the customer. Szendrovits (1975) reduced both manufacturing cycle time and total costs with equal sized batches over all stages for a given order quantity. Transportation costs were treated as sunk costs. Goyal (1976) noted that Szendrovits' model (1975), which involved fixed cost per transport in all stages could use the search procedure to determine the economic production quantity and optimal batches number. Assuming equal batch size at any particular stage and variation of batch number with stage, Goyal (1977a) and Szendrovits and Drezner (1980) determined the economic batch quantity and the optimal batch number at every stage with constant lot size. Also, Goyal (1977b) determined the optimal production quantity for a two-stage production system with unequal batch sizes that follow increasing or decreasing

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geometric series. Moreover, Goyal and Szendrovits (1986) presented a constant lot size model with equal and unequal sized batch shipments between production stages, and solved the model heuristically. Additionally, Vercellis (1999) proposed multi-plant production planning in capacitated self-configuring two-stage serial systems. The resulting mixed {0, 1} linear programming model was solved using LP-based heuristic algorithms. Furthermore, Cachon and Zipkin (1999) examined a two-stage serial supply chain with fixed transportation time and no ordering costs. Most of the literature concerns only two stages (buyer and supplier). However, all stages of the supply chain system must be taken into consideration. Bogaschewsky et al. (2001) developed a model for a multi-stage production and inventory system and established a heuristic method for identifying an upper bound for the total cost of the optimal integer batch number solution and a lower bound for the corresponding production lot size. Subsequently, a scanning process was used to optimize the values of these bounds. In the serial supply chain, a uniform lot size was produced through all stages with a single setup and without interruption at each stage. Partial lots, called batches, may be transported to the next stage on completion. The number of unequal sized batches may differ among stages. Hsiao (2008) solved the one-warehouse multi-retailer problem by the order interval division (OID) and recursive tightening (RT) methods. The proposed solution procedure has a polynomial complexity of $\boldsymbol{O}(n\log n)$ where n denotes the number of retailers involved in the problem.

The Bogaschewsky et al. (2001) model assumed that the production rate at every stage exceeds the product demand rate. Actually, the supply chain may contain a bottleneck. Goldratt (1988) developed synchronous production, which was based on the theory of constraints, and recommended the drum-buffer-rope method to solve the scheduling problem for a production system with a bottleneck. The key principle of the theory of constraints is that effective production management requires focusing on the constraining resources, namely the bottleneck. In synchronous production, the drum is the bottleneck and the mechanism controlling the pace of production. The drum pulls production from earlier stages and pushes it to subsequent stages. In a JIT pull system and a MRP push system, the drum is the final product demand and the master production schedule, respectively.

A constraint is anything that limits an organization, operation, or a system from maximizing its output or meeting its stated objectives. Constraints may be physical such as insufficient labor or plant capacity or non-physical such as poor scheduling or lack of motivation. A bottleneck is also a constraint but its common usage in the supply chain is to describe a situation when the downstream operation has insufficient capacity to accept the upstream load. The capacity of a plant is governed by the physical space, the labor force, financial resources, materials, and machines. In the short-term operating environment, physical space is not normally variable. Plant expansion is considered long-term capacity planning. In the supply chain, one should concentrate on a smooth and regular flow of material through the system rather than attempting to balance the capacity (Goldratt, 1990; Waller, 2003). Operation manager and supply chain coordinator should face the production capacity constraints frequently.

With continuing advances in production technologies and shorter product lifecycles, increasing numbers of companies, in industries as diverse as personal computers, toys, and even agricultural chemicals, are being forced to deal with markdowns. To protect against decline in inventory value, upstream firms only build inventory on receiving orders from downstream firms.

This study investigates a modification of the model of Bogaschewsky et al. (2001). In the multi-stage supply chain, the production rate of at least one stage should be smaller than the demand rate—that is, a bottleneck exists in the supply chain. This investigation adopts the drum-buffer-rope method to keep the bottleneck stage fully utilized and synchronize production during the other stages with the bottleneck. Since the demand and production rate are determined, no buffer is needed to protect the bottleneck against material shortages. Two different uniform lot sizes are produced: one that is pulled through the upstream stages from the bottleneck, and another that is pushed through the downstream stages from the bottleneck. Partial lots, or batches, can be transported to the next stage upon completion. Unequal batch sizes are allowed at each stage, as are different numbers of batches among stages. These unequal batch sizes at each stage follow increasing or decreasing geometric series (Goyal, 1977b). An integer nonlinear programming model is presented that considers setup costs, inventory holding costs and transportation costs for the whole system, and this model is divided into pull and push sub-models. Modify the order interval division and recursive tightening methods of Hsiao (2008), then the lot size division (LSD) and recursive tightening (RT) methods are developed. Based on the LSD and RT methods, the pull and reverse pull method is established to solve the pull and the push sub-models. A numerical example is presented to illustrate the procedures of the pull and reverse pull algorithm.

2. Notations and assumptions

The notations used in this study are listed as follows:

- Q_u upstream lot size pulled through the upstream stages from the bottleneck
- Q_d downstream lot size pushed through the downstream stages from the bottleneck
- m_j number of batches at stage j
- D constant product demand rate (units per unit time)
- P_j constant production rate at stage j (units per unit time)
- h_j holding cost of stage j per unit per unit time
- S_j setup cost of stage j
- F_j fixed transportation cost between stages j and $(j+1)$ ($ per batch)
- $[P_j]^+$ the greater production rate of stages j and $(j+1)$, or, $\max(P_j, P_{j+1})$
- $[P_j]^-$ the smaller production rate of stages j and $(j+1)$, or, $\min(P_j, P_{j+1})$
- R_j production rate ratio of stages j and $(j+1)$, i.e., $[P_j]^+/[P_j]^-$

The 11 assumptions of the model in this study are listed below.

1. The product demand rate is a known constant in the planning period.
2. The product units are infinitely divisible.
3. The supply chain comprises n serial manufacturing stages. Stage $(n+1)$ represents end-customer demand; therefore, $P_{n+1}=D$.
4. The production rate of stage k is the smallest of all stages, i.e., $P_j > P_k$, for $j=1, 2,\ldots,k-1, k+1,\ldots,n$.
5. The production rate of at least one stage is smaller than the demand rate; that is, a bottleneck exists in the supply chain. In the planning period, the supply chain can only produce P_k units of end products for customers. Consequently, there are shortages and lost sales at the demand stage for the end customers.
6. No ordering cost was involved.
7. Backlog and interruption are not permitted at every produc-