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Optimal inventory policies in decentralized supply chains

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ABSTRACT

This paper studies the inventory behavior of *autonomous* and *self-serving* firms in a decentralized retailer–manufacturer serial supply chain. We first analytically characterize the optimal inventory policies for each firm both with and without information sharing, revealing an inherent simple structure of optimal inventory behavior: replenishments are triggered by ultimate customer demand directly. We then consider various extensions: (1) *N*-stage serial systems, (2) batch ordering policies, (3) fixed setup costs, and (4) Markovian customer demand.

1. Introduction

This paper studies inventory behavior in a market economy, in which firms first are autonomous and business is pulled by demand. Every firm aims to maximize its own performance, while working very hard to satisfy its customers' demand. Activities of sales and operations are triggered by downstream orders. In other words, firms optimize their own individual performance based on what is happening downstream where buyers follow some rational decision-making policies for themselves.

We first pause here to post an important question to industry: what is real demand? In practice, orders are often successively passed upstream—the so-called demand evolution (Li, 2008). Facing the customer demand a facility purchases from its supplier based on some popular replenishment policies such as (s, S) or (R, nQ) policies. The order is demand information for its supplier. In other words, the replenishment policies transform facility's demand information (i.e., customer demand) into its supplier's demand information (i.e., facility's orders). This phenomenon propagates along the whole supply chain from downstream to upstream. Firms often use their direct downstream orders as real demand to determine their production and inventory flows. However, these orders can be riskier and illusive, due to self-interest of downstream customers (e.g., minimizing their own costs) (Li, 2008).

The paper promotes the concept of ultimate demand, showing that the real demand actually is ultimate customer demand even with the focal point of each individual self-serving firm. Orders in between supply chain members are "evolved" ultimate demand. Replenishments should be triggered by ultimate demand directly and exactly. In this way we promote a straightforward approach to manage multi-stage *decentralized* supply chains where every firm optimizes its own performance. Our contribution is that we explicitly characterize evolved demand that is compared to original demand; we then derive optimal policies based on demand characteristics and obtain information value based on the comparison. We show that all orders in between supply chain members can be traced back to the origin: ultimate demand.

2. Literature review

Our study is based on three streams of research in the literature: standard single-location systems, information sharing in supply chains, and a demand-focused approach in multi-stage inventory systems. Below we first review key literature results and then specify our contributions for each stream of research.

2.1. Single-location systems

With standard assumptions of a single-location system, linear holding and penalty cost and full backlogging, a base-stock policy is optimal for the linear-ordering-cost case (or no ordering cost) (Karlin, 1958), an (s, S) policy is optimal for the linear-plus-fixed-ordering cost case (or a fixed ordering/setup cost) (Scarf, 1960; Iglehart, 1963), and an (R, nQ) policy is optimal for the batch ordering case (Veinott, 1965). Detailed results of an (s, S) policy explicitly for discrete demand can be found in Veinott and Wagner (1965) and Zheng and Federgruen (1991).

We apply the same above assumptions to every stage in our analyses of multi-stage decentralized supply chains, and extend these results into multi-stage supply chains.

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2.2. Information sharing

Much research in supply chain management is devoted to investigating the value of demand information sharing (Bourland et al., 1996; Gavirneni et al., 1999; Chen et al., 2006; Wu and Cheng, 2008), because demand information sharing is the cornerstone of many supply chain management initiatives in industry such as coordination, joint decision making, and vendor-managed-inventory (Chen et al., 2006; Arshinder et al., 2008).

Bourland et al. (1996) study a two-stage serial supply chain in which the review period of the supplier is not synchronized with his customer and both stages use base-stock policies. The supplier can reduce his demand variability by using the inventory level of the customer at the time of his order review. They then show the supplier with more accurate demand information can reduce his inventory and improve his delivery. Lee et al. (2000) also study a two-stage serial system with AR(1) demand in which both stages use base-stock policies. Using information of realized demand at the retailer, the manufacturer can better estimate his demand (i.e., retailer's orders) with reduced variance. The manufacturer then enjoys information sharing benefits of inventory and cost reduction.

Gavirneni et al. (1999) examine different patterns of demand information sharing between a retailer and a supplier. The retailer faces independent and identically distributed (i.i.d.) demand and places orders to the supplier using an (s, S) policy. With a capacity constraint, the supplier tries to minimize his linear inventory holding and penalty costs in three scenarios with no, partial, or full information sharing. They show that these optimal policies at the supplier are modified base-stock policies. With more information, the supplier can better estimate retailer's orders in different states and thus better setup state-dependent policy parameters. In their computational results, the cost in the full information sharing scenario is always smaller than that in the partial information sharing scenario which, in turn, is smaller than that in the no information sharing scenario. Wu and Cheng (2008) extend these results to a three-echelon supply chain.

All above papers in demand information sharing share one common finding: with more information, the supplier can anticipate his demand more accurately and then setup better policy parameters. Our results confirm the common finding and show precisely the value of information sharing in a multi-stage supply chain.

2.3. Demand-focused approach

Another stream of research in the literature promotes the demand-focused approach to manage multi-stage systems using the concept of echelon stock (Clark and Scarf, 1960). A stage's echelon stock is the inventory position of the subsystem consisting of the stage itself and all downstream stages. Theoretically, the stage has to keep track of all stages in the subsystem in order to calculate its echelon stock. Alternatively, the stage can use its initial echelon stock, ultimate customer demand, and its orders to update its echelon stock. In a notable paper, Clark and Scarf (1960) introduce the echelon inventory policy and show the echelon base-stock policy is optimal for N-stage serial systems with setup cost only at upstream stage N. They use a central-control setting (i.e., a general manager accesses all information and makes all replenishment decisions for the whole system). Chen (1998) generalizes to (R, nQ) policies by decomposing an N-stage serial system into N single-stage systems. He shows that echelon (R, nQ) policies are better than installation (or local) (R, nQ) policies, and the difference is the value of centralized demand information.

These above papers optimize *the system performance*, so we call their systems centralized supply chains. They all assume inventory holding cost rate downstream is higher than upstream and backorder penalty cost incurs only at Stage One. We extend to decentralized supply chains where each firm's performance is optimized individually. In our analysis, inventory holding cost rate downstream may be higher or lower than upstream, and backorder penalty cost incurs at every stage. To put it another way, the N-stage system in their study can be treated as one stage in our decentralized supply chain. The real business network combines many N-stage centralized and decentralized supply chains, so our conclusions for decentralized chains complement those literature results in centralized chains.

Overall, our contribution to the literature is three-fold: (1) we extend standard single-location results into multi-stage supply chains; (2) we analytically present the value of information sharing; and (3) we apply the demand-focused approach to managing decentralized supply chains.

The rest of the paper is organized as follows: Section 3 presents the problem. We then provide analytical results of the two-stage supply chain in Section 4. Section 5 extends to various scenarios: N-stage serial systems, batch ordering policies, fixed setup costs, and Markovian customer demand. Section 6 concludes the paper.

3. The problem

We consider a periodic, infinite-horizon inventory control problem in a two-stage supply chain. The retailer seeks to minimize her inventory related cost, and the objective of the manufacturer is to minimize his inventory related cost as well. In other words, the optimal policy minimizes the average cost per period where there are infinite periods and the discount rate is equal to one. Customer demand in a period is i.i.d. with a mass function, taking nonnegative integers. We use standard assumptions for the retailer: fixed ordering cost, linear holding and penalty costs, and full backlogging. We assume the outside supplier has ample stock.

In each period the sequence of activities is as follows:

(a). Customer demand occurs at the retailer. If her starting inventory exceeds customer demand, she fully satisfies demand and the excessive part is left as ending on-hand inventory, which is charged an inventory holding cost. If customer demand exceeds her starting inventory, she partially satisfies demand and the rest is backlogged; the backorder cost is then charged.

(b). The retailer places an order to the manufacturer, and then on-hand inventory and backorders at the manufacturer are measured in the same way as for the retailer. Finally, the retailer receives a shipment from the manufacturer.

(c). The manufacturer places an order to the supplier, receives a shipment from the outside supplier, and makes his production.

We assume that all happens with no lead time and no setup cost at the manufacturer. If he cannot fully satisfy the retailer's order in a period, the manufacturer is charged a penalty cost for the portion of demand not satisfied from his inventory. The unsatisfied portion is backlogged. We assume the manufacturer can then expedite receiving his raw materials and his own production to make the unsatisfied portion available to the retailer in time (e.g., Ernst and Cohen, 1992). A similar assumption is that the manufacturer can buy the unsatisfied portion from the market with extra cost (e.g., Gavirneni et al., 1999; Lee et al., 2000). We decompose the system in the sense the supplier can provide on-time delivery by using an alternative source: overtime production, expedited delivery, outsource to a third party, or buy