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In recent years, sharing demand-related information has helped many companies improve their supply-chain performance. For example, Milliken and Company, a United States-based textile and chemicals manufacturer, reduced their replenishment leadtime to department stores from 18 to 3 weeks by implementing a strategy called quick response. In this strategy, the retailers place orders and transfer point of sales (POS) data to the manufacturer. This data is used by the manufacturer and its suppliers to better predict the incoming orders and control their inventory. Although the underlying intuition is clear, demand information can help manufacturers better prepare for orders placed by retailers; issues such as when information sharing provides significant cost savings and how manufacturers can use this information most effectively in a make-to-stock production system are not well understood.

To address these issues, we considered a single product, periodic review, two-stage production-inventory system with a single capacitated manufacturer and a single retailer facing independent demand and using an order-up-to inventory policy. Assuming negligible set-up cost and change-over time, the manufacturer's production capacity is proportional to the time available for production. Because many companies place orders periodically but they can share information with their partners continuously, we assume that the manufacturer receives demand information from the retailer even during time periods in which the retailer doesn't place orders.

Specifically, we assume that the retailer has a fixed ordering interval. That is, every T time periods (e.g., four weeks) the retailer places an order to raise her inventory position to a target level. The manufacturer receives demand information from the retailer every τ units of time, $\tau \leq T$. For instance, the retailer places an order every four weeks but provides demand information every week. We refer to the time between successive orders as the *ordering period* and the time between successive information sharing as the *information period.* This is clearly the case in many industries, where POS data can be shared almost continuously while orders are placed periodically. Of course, while information can be shared almost continuously (e.g., every minute) decisions are typically made less frequently (e.g., every week). Thus, information periods refer to the time intervals between successive use of the information provided by the retailer to the manufacturer.

A recent paper by Simchi-Levi and Zhao (2000) studies this model in a finite time horizon. They show that by sharing demand information, the manufacturer can reduce its inventory cost substantially, while maintaining the same service level to the retailer.

The objective of this paper is to quantify the impact of information sharing on the manufacturer in infinite time horizon. For this purpose, we first characterize the manufacturer's optimal production-inventory policy with information sharing under both the discounted and average cost criteria. Then, we identify situations under which information sharing is most beneficial. Finally, we quantify the impact of frequency and timing in which demand information is shared on the manufacturer.

The impact of information sharing on a capacitated manufacturer has been analyzed by several authors. Aviv and Federgruen (1998) analyze a single-supplier, multiretailer system where retailers face random demand and share inventories and sales data with the supplier. Because it is quite difficult to find the optimal policy, these authors use heuristics. In the paper, they compare the performance of a traditional, decentralized system to a supply chain in which information is shared continuously but decisions are made individually (i.e., by the different parties). Their focus is on minimizing long-run average cost. Aviv and Federgruen report that information sharing reduces system-wide cost by 0 to 5%. They also show that information sharing could be very beneficial for the supplier.

The paper by Gavirneni et al. (1999) analyzes a two-stage supply chain with a single capacitated supplier and a single retailer. In this periodic review model, the retailer makes ordering decisions every period, using an (s, S) inventory policy and transfer demand information every time an order decision is made, independent of whether an order is made. Assuming zero transportation leadtime, they show that the benefit; i.e., the supplier's long-run average cost savings, due to information sharing increases with production capacity and it ranges from 1 to 35%.

Our paper is different from the work described above in the way that we allow demand information to be shared at any time, while in Gavirneni et al.'s model, information is shared only at times when order decisions are made and in Aviv and Federgruen's model, information is transferred only at the end of each basis period of equal length.

In our model we assume that the manufacturer has the following cost structure: inventory holding cost is charged for each information period while penalty cost is charged only at the end of each ordering period for each unit that the manufacturer cannot satisfy. This implies that the earlier the manufacturer produces during an ordering period, the longer she will carry this inventory, thus the higher the inventory holding cost she has to pay. On the other hand, delaying production too much may result in backlogging and, thus, high penalty costs because of the finite production capacity.

The sequence of events in our model is as follows. At the beginning of an information period, the retailer transfers POS data of the previous information period to the manufacturer. Upon receiving this demand information, the manufacturer makes a production decision for this information period. Similarly, at the beginning of an ordering period the retailer reviews her inventory and places an order to raise the inventory position to the target inventory level. The manufacturer receives the order from the retailer, fills the order as much as she can *from inventory,* and then makes a production decision for the current information period. If the manufacturer cannot satisfy parts of a retailer order from her inventory, she can get the missing amount from an *outside source* who has an unlimited supply. Either way, the total order arrives at the retailer facility in no time. Thus, transportation leadtime is assumed to be zero. When the manufacturer uses the outside source, she has to return the borrowed items to the outside source at the beginning of the next ordering period.

Throughout the paper, we compare the following two production systems: the traditional make-to-stock system without information sharing (where the manufacturer only knows the order history) and the system with information sharing. In the traditional system, we assume the manufacturer knows the external demand distribution in one ordering period; whereas in the system with information sharing, the manufacturer knows external demand distribution in each information period.

To find the optimal policy for the manufacturer with information sharing, we formulate the manufacturer's inventory control problem as a Markov Decision Process with unbounded cost functions and periodically varying parameters. Recent research on the periodical inventory system (Aviv and Federgruen 1997, Kapuscinski and Tayur 1998) report that the cyclic order-up-to policy is optimal under the discounted and average cost criteria. One of their assumptions is that the manufacturer has both inventory holding and penalty costs in each time period. If there is no penalty cost in some time periods, their results cannot be applied. Unfortunately, in our information sharing model, there is no penalty cost in time periods in which the manufacturer only receives demand information but not orders from the retailer. Thus, we need to extend their results to this more general, periodical inventory system by aggregating information periods into ordering periods and taking advantage of the fact that at the end of each ordering period, the manufacturer incurs penalty costs if demand cannot be satisfied from stock.

Following the vanishing discount method, we provide a simple proof for the optimality of the cyclic order-up-to policy under average cost criterion by applying the concept of the Blackwell optimal policy. The method developed in this paper is quite general and can be used to prove average cost optimality for policies with critical numbers, such as an (s, S) policy, as long as these policies are optimal under the discounted cost criterion.

One of the most important and difficult component of the analysis is to show that the cyclic order-up-to policy has finite steady-state average cost under general conditions. The difficulty comes from the complicated transition matrices of the Markov chains associated with the policy. To overcome this difficulty, we develop a three-step approach by starting with an order-up-to zero policy. First, we generalize Foster's criterion and use it to show the finite steady-state average cost for an order-up-to zero policy. Then, we extend the result to a cyclic order-up-to policy with returns. In this policy, the manufacturer returns the excessive inventory if the initial inventory position at the beginning of any time period is higher than the target inventory level. Finally, we prove the finite steady-state average cost for a general cyclic order-up-to policy by relating two Markov chains, one associated with a cyclic order-up-to policy with returns and the second associated with a general cyclic order-up-to policy. The proof is based on the following two observations: First, for the same stream of demand, the difference between these two Markov chains characterizes a process with finite state space. Second, for two arbitrary irreducible Markov chains, if their difference process has finite state space, then properties such as positive recurrence and finite steady-state average cost can be transferred from one Markov chain to another.

After proving the structure of the optimal policy, the next question is whether one can identify the relationship between the optimal order-up-to-levels of two consecutive information periods. Intuitively, delaying production until close to the end of the ordering period should allow the reduction of inventory holding costs. The risk, of course, is that delaying production too much may lead to a shortage, due to the limited production capacity. In the paper, we prove that if demand in any information period can be no larger than production capacity, then in any two consecutive information periods within one ordering period, the optimal order-up-to level of the earlier information period is no larger than that of the later time period. This is consistent with our intuition that if we have enough production capacity, postponing production as much as possible is profitable. In fact, in our computational analysis, we find that even if this condition doesn't hold, the property is still true in almost all the cases except when production capacity is tightly constrained (e.g., capacity over mean demand is no more than 1.2).

To develop insights about the benefits of information sharing and identify situations where information sharing provides significant cost savings (compared to supply chains with no information sharing), we conducted an extensive computational study using infinitesimal perturbation analysis (IPA) (see Fu 1994, Glasserman and Tayur 1995). We examine cases with variation on the following parameters: production capacity, the number of information periods in one ordering period, and the time when information is shared.

The computational study reveals that in a make-to-stock production system, the percentage cost savings increase as production capacity increases. Indeed, percentage cost savings increase from about 3 to 35% as capacity over mean demand increases from 1.2 to

3 for various external demand distributions. This is quite intuitive because as capacity increases, the optimal policy would postpone production as much as possible and take advantage of all information available prior to the time production starts. For instance, in case of infinite capacity, it is optimal to wait until the last information period to produce enough to satisfy all demand realized so far, plus an additional amount based on solving a newsboy problem. Similarly, if the production capacity is very limited, then information is not that beneficial because production quantity is mainly determined by capacity, not based on realized demand. Finally, our computational study reveals that information sharing has no impact on fill rate (i.e., information sharing and no information sharing have almost identical fill rates, given the same penalty and inventory cost for both cases).

To understand the impact of the frequency of information sharing, we studied the percentage cost savings as a function of the number of information periods in one ordering period. The number of information periods, N, varies from 2, 4, 6, to 8, while the length of the ordering period is assumed to be fixed in all cases. Thus, the demand distribution during the entire ordering period is fixed, assumed to be Poisson with parameter λ, and demand in a single information period is Poisson with parameter λ/N. Total production capacity and inventory holding cost per item in the entire ordering period are kept constant and equally divided among the different information periods. Our computational analysis illustrates that

• As the number of information periods increases, the percentage savings increase.

• Most of the benefits from information sharing are achieved within a few information periods; e.g., four information periods. That is, the marginal benefit is a decreasing function of the number of information periods. Specifically, the benefit achieved by increasing the number of information periods from four to eight is relatively small.

Finally, we study the impact of the time when information is shared, given that the retailer only shares demand information once with the manufacturer in one ordering period. The trade-off is clear: As the manufacturer postpones the time of information sharing, she obtains more demand information but she is also running out of her production capacity. To identify the best timing of information sharing and the impact of parameters such as production capacity and target fill rate, we study the manufacturer's total cost as a function of the time when information is shared. We observe:

• As information sharing is delayed, manufacturer's cost first decreases slowly and then increases sharply.

• When capacity is very large relative to mean demand; e.g., capacity over mean demand equals five, it is appropriate to postpone the time of information sharing to the last production opportunity in this ordering period; e.g., 0.9 of one ordering period. On the other hand, when capacity is relatively tightly constrained; i.e., capacity over mean demand is no more than two, the manufacturer's cost is less sensitive to the timing of information sharing. For instance, if capacity over mean demand equals two, the manufacturer's cost remains almost constant when the time of information sharing varies from 0.4 to 0.9.

References

Aviv, Y., A. Federgruen. 1997. Stochastic inventory models with limited production capacities and periodically varying parameters. *Probab. Eng. Inform. Sci.* **11** 107–135.

——, ——. 1998. The operational benefits of information sharing and vendor managed inventory (VMI) programs. Working paper, Washington University, St. Louis, MO.

Fu, M. C. 1994. Optimization via simulation: A review. *Ann. Oper. Res.* **53** 199–247.

Gavirneni, S., R. Kapuscinski, S. Tayur. 1999. Value of information in capacitated supply chains. *Management Sci.* **45** 16–24.

Glasserman P., S. Tayur. 1995. Sensitivity analysis for base-stock levels in multiechelon production-inventory systems. *Management Sci.* **41** 263–281.

Kapuscinski, R., S. Tayur. 1998. A capacitated production-inventory model with periodic demand. *Oper. Res.* **46** 899–911.

Simchi-Levi, D., Y. Zhao. 2000. The value of information sharing in a two-stage supply chain with production capacity constraints. Working paper, Northwestern University, Evanston, IL.