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Optimal inventory policies with non-stationary supply disruptions and advance supply information

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ABSTRACT

We consider the production/inventory problem of a manufacturer (or a retailer) under non-stationary and stochastic supply availability. Although supply availability is uncertain, the supplier would be able to predict her near future shortages – and hence supply disruption to (some of) her customers – based on factors such as her pipeline stock information, production schedule, seasonality, contractual obligations, and non-contractual preferences regarding other manufacturers. We consider the case where the information on the availability of supply for the near future, which we refer to as advance supply information (ASI), is provided by the supplier. The customer demand is deterministic but non-stationary over time, and the system costs consist of fixed ordering, holding and backorder costs. We consider an all-or-nothing type of supply availability structure and we show the optimality of a state-dependent (s,S) policy. For the case with no fixed ordering cost we prove various properties of the optimal order-up-to levels and provide a simple characterization of optimal order-up-to levels. For the model with fixed ordering cost, we propose a heuristic algorithm for finding a good ordering strategy. Finally, we numerically elaborate on the value of ASI and provide managerial insights.

1. Introduction and related literature

Numerous success and failure stories have taught us that supply chains need to take potential supply disruptions into account in the planning phase, rather than 'fire-fighting' when disruptions take place. The supply process in a supply chain can be disrupted for various reasons, which can be classified into two groups: i) unpredictable disruptions, which arise from natural disasters, terrorist attacks, accidents, and the like, and ii) predictable disruptions, which basically originate from capacity restrictions and scarcity of some resources at the supplier. Further, a predictable disruption might be either due to a temporary total lack of the supplier's production capacity (in which case none of her customers are satisfied), or the supplier's choice in allocating her restricted capacity to other manufacturers and/or products. The supplier would possibly be able to predict her near future shortages – and hence supply disruption to (some of) her customers – based on factors such as her pipeline stock information, production schedule, seasonality, contractual obligations and non-contractual preferences regarding other manufacturers, and the like. Nevertheless, a predictable disruption might remain unpredictable to the manufacturer (or the retailer) if the supplier does not inform him – at least to a certain extent – about this disruption. We refer to such information concerning future disruptions that are known to the supplier as advance supply information (ASI). The supplier might want to provide the manufacturer with ASI for several reasons including reputation and improving collaboration.

In this paper we consider the production/inventory problem of a manufacturer (or a retailer) under non-stationary stochastic supply uncertainty and availability of ASI. The supply chain environment that we consider consists of a manufacturer facing non-stationary deterministic demand, and an outside supplier with uncertainties in the delivery times and amounts. Novel features of our model are that (1) the supply availability over the planning horizon is time dependent, and (2) the supplier provides the manufacturer information regarding the supply conditions over a limited specified horizon (the ASI horizon). Moreover, since both the customer demand sequence, and the supply availability structure is time dependent, our model can also be used to capture possible correlations between the customer demand and the disruption duration in supply.

The supply structure that we consider is of all-or-nothing type and is similar to a clearing process: in a given period, the order placed by the manufacturer along with its backorders is supplied with a

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probability that depends on the period. Under this environmental setting, the manufacturer's problem becomes determining the optimal order amount in each period that minimizes expected linear holding and backorder costs and the cost of ordering over the planning horizon. As the manufacturer keeps track of the supply availability information provided by its supplier, any optimal policy should be a function of ASI as well as the time dependent nature of supply uncertainty. In this article we characterize the structure of the optimal policy and provide managerial insights on the impact of ASI on the optimal system performance. To the best of our knowledge, our paper is the first one that provides an exact and near-explicit expression for optimal order-up-to levels as a function of the supply information.

The environment described above is suitable for the planning problem of a parts manufacturer where customer orders are the firm production quantities dictated by an upstream stage through a master production schedule. The parts manufacturer, now facing deterministic customer orders, needs to plan its own order quantities from an outside supplier whose delivery performance is time dependent and uncertain. The parts manufacturer tries to reduce the supply uncertainty by receiving the supply availability information from the supplier a number of periods in advance. Under the assumption of all-or-nothing type supply structure, ASI is equivalent to knowing the timing of the supply availability (when the order is fully delivered and any backorders are cleared), and supply unavailability (nothing is delivered) periods during the ASI horizon. From this perspective our system also resembles a supply system where the inter-delivery times are non-stationary random variables, the supplier keeps track of the manufacturer's inventory position and a partial knowledge of the delivery times is revealed to the manufacturer.

Papers in production/inventory literature that model uncertainties in the supply side can be divided into three research tracks. Papers in the first track model supply uncertainty by considering random durations in which supply is either completely unavailable or completely available (our paper falls into this group). [17] and [18] are early examples of allowing random supply disruptions in inventory literature. In both of these papers supply availability and unavailability durations are respective exponential random variables and the inventory models follow assumptions of Economic Order Quantity (EOQ) model. In particular, the demand process is continuous and stationary over time. [17] allows a replenishment (when the supply is available) when the inventory level drops to zero, whereas [18] incorporates a possibly non-zero reorder level and multiple suppliers. Under a Poisson demand process and fairly general availability and unavailability durations, [15] evaluates an (s,Q) type inventory policy. [8] considers a periodic review variation of the model in [17] where the supply unavailability durations are non-stationary random variables, and the demand quantities in successive periods are dynamic deterministic values. [8] presents a newsboy-like expression for obtaining the optimal order-up-to levels.

The second research track treats supply uncertainty as randomness in yield, where the quantity received is a random fraction of the quantity ordered starting with the pioneering work of Karlin, Yano and Lee, Gerchak et al., Henig and Gerchak, Wang and Gerchak, and Hsu and Bassok [13,23,6,9,22,10] which presents various production/inventory model incorporating random yield. In a recent article Yeo and Yuan [24] consider a model with random yield and demand cancelation, and show that the optimal ordering policy has a reorder point structure.

In the last research track, the production capacity, rather than the supply is considered to be random. Note that there is a subtle difference between uncertainty in supply and randomness in production capacity. In supply uncertainty models, when the supply is available it is assumed to be fully available. Therefore, supply uncertainty often occurs not as a constraint on the amount that can be ordered, but as an external factor that affects the quantity received (either nothing or a fraction of the ordered amount is received during the unavailability duration). In random capacity models on the other hand, the maximum amount that can be ordered (or produced) is a random variable, and hence the treatment of models with finite (but random) capacity is quite different. [4,11,7] consider periodic review inventory problems under random capacity. In these papers, demand and supply processes are assumed to be stationary. [5] considers the same problem, but allow the distribution of capacity to vary according to a Markov chain.

In the supply uncertainty literature, information on availability of future supply is typically modeled through considering supply uncertainty as a Markov process. In these models the probability distribution of supply availability in the next period depends on the current availability state (see, for example, [16,19,21,3]). We differ from the literature by explicitly including the supply information for a number of periods in our state definition. Among the papers that treat production capacity as a random variable, [12,1] explicitly consider the existence of advance information on production capacity in their models. In these papers the evolution of capacity information follows stationary processes. Main differences of our work from previous papers that incorporate supply or capacity information in their models are that we allow the supply process to be non-stationary, and we provide exact and near-explicit expressions for the optimal policy parameters in a finite horizon setting.

In this article we make four major contributions: (1) we consider non-stationary supply uncertainty and model advance supply information, (2) we provide characterization for the optimal policies and when the fixed cost is zero we provide easy-to-compute, near-explicit solution for the optimal base stock levels as a function of ASI, (3) we propose and test a heuristic solution for the non-zero fixed cost case, and (4) we provide managerial insights on the value of ASI.

The rest of the paper is organized as follows. In Section 2 we introduce our dynamic programming model and analyze the form of the optimal ordering policy. In Section 3 we consider the model with no fixed cost and analyze the optimal policy. In Section 4 we present a heuristic approach for the model with fixed ordering cost and discuss the performance of the heuristic. In Section 5 we provide a comprehensive numerical analysis. We conclude the paper in Section 6.

2. Description of the model

In this section we present the dynamic programming model for the problem and provide the optimal ordering policy. We first describe the structure of supply uncertainty and ASI. The following notation is to be used throughout the paper but we introduce additional notation as need arises.

N	number of periods in the planning horizon,
D_n	demand in period n for $n=1,2,\ldots,N$,
h	holding cost per unit per period,
b	backorder cost per unit per period,
A	fixed ordering cost
M	Length of the ASI horizon, $M\geq 1$
p_n	probability that supply is fully available in period n.

2.1. Structure of supply uncertainty and ASI

Supply uncertainty has an all-or-nothing type structure, such that in a given period supply is either fully available or completely unavailable. When supply is available in a given period we denote this period as a *supply period*. Supply availability probability is non-stationary over the planning horizon and supply availability in a period is independent of other periods. In addition, the supplier provides supply availability information to the manufacturer regarding the future periods. Therefore, manufacturer may reduce the uncertainty with the help of ASI. Suppose that at the beginning of period