Decision Support Systems 53 (2012) 320–330

Contents lists available at SciVerse ScienceDirect

Decision Support Systems

journal homepage: www.elsevier.com/locate/dss

An inventory model with capacity flexibility in the existence of advance capacity information

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ARTICLE INFO

Available online 25 January 2012

Keywords:
Advance capacity information
Inventory management
Outsourcing
Order-up-to policy

ABSTRACT

In this paper we study the inventory/production problem of a firm that uses operational level outsourcing to hedge against uncertainty. We consider an environment in which the maximum amount that can be produced in a period, the regular capacity of the system, is uncertain, but information on its realization (which we call the "advance capacity information" (ACI)) is available. We model the uncertainty in regular capacity, and present an ACI process that tracks and updates the information on the availability of the regular capacity. For this system we propose an ACI-dependent order-up-to level policy. We characterize the optimal solution under the order-up-to level policy, and through a numerical study we derive managerial insights with respect to the benefits of using outsourcing option and ACI.

1. Introduction

In planning and managing inventory/production systems, two main strategies can be used to manage uncertainty: gradually building inventory to hedge against possible future shortages, or temporarily increasing the capacity by *purchasing* extra capacity. The ability to adjust the total capacity temporarily by acquiring extra resources, such as subcontracting, overtime production, hiring temporary workers, leads to capacity flexibility. In the existence of capacity flexibility, inventory/production related costs may be reduced by managing the capacity and inventory in a joint fashion. We consider an inventory/production system under ACI with flexible capacity, where flexibility is obtained with an outsourcing option to replenish the inventory to reach the target inventory level in any planning period.

The benefit of using outsourcing can be substantial to hedge against capacity and/or demand uncertainties caused by fluctuating demand, unreliable suppliers, and disruptions in in-house factors such as the work force and machinery. The capacity of a production system can be uncertain due to breakdowns or unplanned maintenance activities of machinery. Also, the resource can be shared by several items, and due to randomness in yield and rework activities, the capacity allocated to an item may exhibit random fluctuations. Ciarallo et al. [6] is the first paper in the literature to consider uncertainty in the production/inventory capacity. The objective of this study is to analyze the operational level outsourcing and inventory/production decision making for a manufacturer with limited uncertain capacity and volatile demand.

Our work is related to the papers in the capacity management literature that attempt to exploit the interactions between capacity planning and inventory/production decisions. Capacity management problems have been studied at different levels of decision making. Research on tactical outsourcing mostly has been concentrated on the strategic questions related to price setting, capacity investing, and contract writing (Yang et al. [20]). Some papers that deal with capacity investing are Rocklin et al. [14], Eberly and VanMieghem [7] and Angelus and Porteus [3]. Rocklin et al. [14] consider a make-to-order system where capacity can be reduced or increased at exogenously set unit prices. For a system where capacity is costly reversible, such as costly labor lay-offs, they give conditions under which the optimal capacity plan is a *target interval policy*. With the target interval policy it is optimal not to change the capacity as long as it is in the region defined by an interval. On the other hand, if the capacity is outside the interval, it is optimal to adjust the capacity to the nearest point on the boundary of the interval. In other words, if the initial capacity is below the lower target limit, then the aim is to bring the capacity up to that limit. And if the initial capacity is above the upper target limit, then the aim is to bring the capacity down to that limit. Otherwise, no capacity changes are made. Eberly and VanMieghem [7] generalize this result to multiple resources with linear or convex adjustment cost functions and concave operating profit functions for both finite and infinite planning horizons. Angelus and Porteus [3] study optimal capacity and production planning for a make-to-stock system, where capacity can be reduced, as well as added. They consider both short life cycle products and products that can be carried over to future periods, incurring holding costs for the latter. In both cases a target interval policy is shown to be optimal.

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0167-9236/$ – see front matter
doi:10.1016/j.dss.2012.01.008

They characterize the target intervals for short life cycle products, assuming demand first increases stochastically, then decreases.

In these studies capacity expansion and reduction are strategic decisions leading to the ownership of the capacity; there is either a salvage value or price for capacity reduction at the end of each planning period for unsold units/unused capacity. In our setting we do not consider the ownership of the capacity, but consider the usage of the capacity temporarily. The reader is referred to Van Mieghem [19] for a review of the literature on strategic capacity management under uncertainty.

In a contract setting environment Kamien and Li [9] present conditions under which tactical outsourcing mechanisms should be carried out, and they show that such mechanisms have the effect of production smoothing. Van Mieghem [18] uses a game-theoretical model to analyze outsourcing conditions for different types of contracts between a firm and its subcontractor. Tan [15] analyzes an environment with a capacitated producer and a capacitated subcontractor. The availability of the subcontractor is subject to uncertainty; however, a level of availability is guaranteed by a contract. The producer decides how much to produce and how much to subcontract at a given time using a threshold-type policy that depends on the state of the inventory. Our work is different from this line of work in that we do not consider contracting issues, but we assume that there is a given contract (that sets the price of outsourcing option) with an exogenous supplier.

Bradley [5] considers a continuous time inventory/production model to minimize the average cost. The inventory can be replenished through two possible resources, in-house production and a subcontractor, both with finite capacity. Assuming that the manufacturer uses a base-stock policy to control replenishment from the two sources, the authors propose using a Brownian approximation of the optimal control problem for determining the fixed capacity level and optimal production quantities. They show through numerical studies the value of the outsourcing option. Tan and Gershwin [17] study a similar continuous-time model with several subcontractors having different unit costs and capacities. We differ from these papers in two respects: (1) we consider a periodic review setting, and (2) we explicitly model capacity uncertainty.

Yang et al. [20] consider a Markovian in-house production capacity, and the outsourcing option with setup cost. They show that the firm's optimal outsourcing policy is a capacity-dependent (s,S) policy. For the case of deterministic capacity they show that the optimal production policy is a modified base-stock policy. In their study they make the assumption that the outsourcing decision is made before the production decision and the outsourced amount is fully used, whereas in our setting the outsourcing and production decisions are simultaneous, enabling more flexible use of the outsourcing option.

Tan and Alp [16] consider the usage of contingent capacity in terms of temporary workers. Assuming limited contingent and in-house capacity they show that the optimal operational policy, for any given fixed permanent capacity level, is of state-dependent order-up-to type. In a similar setting Alp and Tan [1] also consider the permanent workforce size to be utilized through the planning horizon as a decision variable. Including fixed costs for both initiating production and for using contingent capacity, they provide the optimal solution to the single-period problem. For the multi-period problem they characterize the optimal policy for some special cases, and argue that the optimal policy does not have a simple form. In Pac et al. [11] this model is extended to include uncertainty in the contingent capacity received from external resources, where a certain number of workers can be guaranteed through contracts at a reservation cost. The decisions are the number of contracted contingent workers, the optimal level of permanent capacity, the number of workers to be hired, and the quantity of production in each period. Pinker and Larson [12] consider a setting where holding inventory is not allowed and the absenteeism of regular workers is expected. The number of regular and contingent workers is fixed for the entire planning horizon, but the capacity is adjusted by using the labor force overtime (both permanent and contingent workers). Mincsovics et al. [10] extend the model in Alp and Tan [1] to include constant lead time associated with the acquisition of contingent capacity. They characterize the optimal policy for the operational decisions and the optimal permanent capacity level. They prove that the inventory, the pipeline contingent capacity, the contingent capacity to be ordered, and the permanent capacity are economic substitutes. The value of flexibility remains considerable even when the capacity acquisition lead time is relatively long.

Obtaining the true optimal policy for a system facing volatile demand in the existence of outsourcing option is difficult. Even for a system where the regular capacity is deterministic and stationary, the form of the optimal policy is complicated (Alp and Tan [1]). We propose an ACI-dependent order-up-to level policy with flexible capacity in which whenever the target base-stock level cannot be reached using the currently available capacity at a given period, the short amount can be bought from an exogenous supplier.

Our work also is related to the papers that model advance capacity information. This line of work is more recent and scarce. Altug and Muharremoglu [2] and Jaksic et al. [8] incorporate advance information on capacity in the inventory replenishment problem. In Altug and Muharremoglu [2] advance supply information is available in terms of capacity forecasts provided by the supplier. They model the evolution of the capacity availability forecasts via the Martingale Method of Forecast Evolution, and show that state-dependent base-stock policies are optimal. In Jaksic et al. [8] the ACI for a number of future periods is not updated every period, but it is fixed after it has been observed. They show that the optimal ordering policy is a state-dependent modified base-stock policy, and that most benefits of using ACI can be reached with only limited future visibility.

In an environment with uncertain capacity, advance information has the potential to improve inventory-related decision making, either by inflating the order to avoid shortages in future periods, or avoiding unnecessary inventory holding costs. The capacity of the inventory system we consider is the maximum amount that can be produced in a period, which we call the *regular capacity* of the system. We assume that the regular capacity for the inventory process is uncertain and non-stationary, but the manufacturer observes a signal on its realization in advance.

Our contributions in this paper can be summarized as follows: We first model the uncertainty in regular capacity, and present an ACI process that tracks and updates the information on the availability of the regular capacity. Then, we discuss the operating characteristics of the inventory system and propose an ACI-dependent order-up-to level policy. We develop an expression for the average cost of the system, and characterize the optimal solution under the order-up-to level policy. Then using the first order conditions and the properties of the optimal solution we describe a solution procedure. Finally, we derive managerial insights through a numerical study. The rest of the paper is organized as follows. We introduce our model in Section 2. The solution procedure is presented in Section 3. The results of the numerical study and the managerial insights are given in Section 4.

2. Description of the model

In this section we present and analyze a model where the maximum amount that can be produced in a period (the regular capacity of the system) is uncertain, but information on its realization (which we call the “advance capacity information” (ACI)) is available one period in advance. We first model the uncertainty in regular capacity, and present an ACI process that tracks and updates the information on the availability of regular capacity. Then we discuss the operating characteristics of the inventory system and propose an ACI dependent order-up-to level policy.