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Stock-level dependent ordering of perishables: A comparison of hybrid base-stock and constant order policies

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ABSTRACT

In practice, traditional stock-level dependent policies, like base-stock policies (BSP) and constant order policies (COP), are commonly used for replenishing inventories of perishable products at retailers. These policies are preferred for being easy to implement: they only require information on the total number of products in stock, but not differentiated by their age. In this paper, we analyze a number of new and existing hybrid BSP-COP policies. These policies have different complexities, but, so far, they have not been systematically compared with respect to their performance. By simulation-based optimization, the parameter values of the policies are determined. For this purpose, search ranges for the parameter values are provided. Based on an extensive set of experiments, insights are gained on when to apply which policy. The results show that two newly proposed enhancements of traditional base-stock policies, in particular, perform well and can be recommended for practical implementation.

1. Motivation

Product waste is a serious problem in food supply chains. The political agenda has defined individual targets for the reduction of these losses at all stages of the supply chain (Buzby et al., 2009; Gustavsson et al., 2011). At the same time, perishable product inventory management is known to be a notoriously difficult problem with many additional challenges when applied in supermarket practice (van Donselaar et al., 2006). Even in very stylized problems, except for simple special cases (Fries, 1975; Nahmias, 1975), the structure of the optimal policy is unknown and depends on a large state space, including all outstanding orders and the current stock differentiated by shelf life. Therefore, several simpler (structured) policies have been proposed in the literature (recent reviews are provided in Nahmias, 1982, 2011; Karaesmen et al., 2011; Bakker et al., 2012). However, there is no common understanding of the performance of these policies if compared with each other and a lack of recommendations on which policy to use under what circumstances.

Base-stock policies (BSP) and constant order policies (COP) have been well studied and applied for controlling inventories of non-perishable and perishable products. BSP was investigated by Cohen (1976) for the first-in-first-out (FIFO) inventory depletion and two-period shelf life case. COP was suggested in Brodheim et al. (1975). Both policies and refinements have attracted some research for lost sales inventory problems (Bijvank and Vis., 2011; van Donselaar et al., 1996). Both the base-stock and the constant order policy were used as benchmarks for a dynamic, state-dependent policy in a.o. Minner and Transchel (2010). Haijema (2014) compares BSP with optimal stock-age dependent ordering as obtained by Stochastic Dynamic Programming (SDP). Using BSP, that paper also studies potential improvements by optimal stock-age dependent issuance, and stock-age dependent disposal of products in stock. A stock-age dependent policy is rather complex to solve and to implement.

As BSP and COP are often used, but traditionally designed for controlling non-perishables, we are interested in modifications of BSP and COP. Hence we focus on the many policy options in-between BSP and COP; we call the in-between-policies hybrid BSP-COP policies. BSP and COP can be significantly improved in many settings by a generalized policy named the $(s, S, qmin, Qmax)$ policy, or, in short, sSqQ (Haijema, 2013). This policy is a BSP with base-stock (order-up-to) level S and a reorder point s, extended with a minimal order quantity $qmin$, and a maximal order quantity $Qmax$. sSqQ represents a class of order policies. Related policies in that class are obtained by putting constraints to the parameter values. For example, sSqQ can be tuned such that it mimics BSP or COP, or an in-between policy. If $s = S$, $qmin = 0$ and $Qmax = S$, then sSqQ is a pure BSP. If $qmin = Qmax$ and $s = \infty$, sSqQ boils down to COP. When all four parameters $(s, S, qmin, Qmax)$ are optimized, the

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computational burden may not always outweigh the cost savings compared to the single-parameter policies BSP or COP. The idea in Haijema (2013) of formulating the sSqQ policy came from numerical results on the structure of optimal ordering policies as obtained by SDP. Compared to BSP, an optimal SDP policy seems to have, in many settings, smoother order quantities. Haijema (2013) did not show results for all policies covered by sSqQ, and thus did not study the role of each parameter in detail nor the impact of dropping a parameter.

In this paper, we investigate all policies within the class of $(s, S, qmin, Qmax)$ policies, and new policies that may improve existing policies while having less than four parameters. In particular, we modify the structure of BSP (and COP) such that it generates more smooth orders and thus reduces risk of outdating by preventing to have simultaneously many products in stock close to their expiration date. In Section 2, we describe the structured policies included in our numerical investigation in detail. Next to existing policies, like BSP and COP, we introduce a variety of policies that either smooth the order quantity or potentially result in order skipping. The motivation for order smoothing comes from the observation in Haijema (2013) that an optimal order policy can be approximated by adding a minimum and a maximum order quantity. Although the focus is on a stationary problem setting with no fixed ordering cost, the inclusion of a reorder point s is considered as a method to improve order policies. The reorder point results in no order being placed when the inventory position is at or above s. In this way, one can reduce the risk of outdating because consumers who would normally take the freshest items available are forced to accept older products. As the complexity of finding optimal parameter values increases with the number of parameters, we cluster the policies according to the number of parameters.

A simulation study is executed with experiments that vary in lead time, maximal shelf life, mean demand, variance-to-mean ratio of demand, the fraction of customers depleting inventory according to FIFO or LIFO respectively, and the cost ratio of unit shortage and unit waste costs. All experiments deal with stationary demand and have a review period of one day. In particular, we investigate the improvement in finding a costs-optimal tradeoff between unmet demand and product waste, which are the main performance measures for inventory management at retailers, and the degree of order smoothing. Therefore the study focusses on shortage costs and waste costs, which includes procurement costs. For each experiment, the policies are optimized by a simulation-based global search. In particular, if the policy involves two or three control parameters, the (potential) existence of multiple local optima complicates the search. To facilitate a full enumerated search process, we present search ranges for the parameters. Nandakumar and Morton (1993) and Cooper (2001) provide lower and upper bounds for the optimal order-up-to level when lead times are zero and inventory issuing follows FIFO. Their main idea and approach is based on using myopic, newsvendor type expressions. We follow this idea to extend the existing bounds to our more general setting with positive lead times and mixed inventory issuing. However, the ranges cover a larger spectrum of applications and therefore are less tight than the ones known for simpler cases. A post-optimization procedure is applied to check the quality of the ranges and overcome too restrictive limits.

The main contribution to the existing literature is fourfold: (1) an overview of existing stock-level dependent policies is provided, (2) new stock-level dependent policies that improve BSP and COP are introduced, (3) search ranges are provided for optimizing the parameter values, including settings with a positive lead time (problems with positive lead time and perishable products, in particular, are rather underinvestigated in the literature Karaesmen et al., 2011), and (4) all policies are compared by using an extensive set of 11,177 experiments; for 1194 experiments, benchmarks obtained by an optimal (stock-age dependent) SDP policy are reported.

Section 2 states the model assumptions and formally defines the order policies included in the comparison. Section 3 reports the experimental design and numerical results, both with respect to cost and computational performance. Section 4 compares the policies against an optimal stock-age dependent policy. Section 5 summarizes the main findings and outlines areas for further research.

2. Model and policies description

2.1. Assumptions and notation

We consider a periodic review, single-product stochastic (stationary) inventory control problem of a perishable product. After receipt, each unit of the product has a constant and deterministic shelf life of m periods. Inventory is replenished periodically with a deterministic lead time of L periods. Both L and m are expressed as an integer multiple of the basic review period. If not sold at or before its fixed expiration date, a product is discarded at a unit waste cost c_w, which includes the procurement cost. In most supermarket settings, fixed ordering cost can be neglected because perishables are replenished on a daily basis or because transport costs are shared over many SKU's. The short shelf life of products prevents overstocking and thus makes holding costs less relevant to retailers. Demand per period is split into two stochastic discrete demand distributions: one distribution relates to customers who take the youngest products from the shelf, and another distribution models the demand by customers who are satisfied with the oldest products in stock. The first category is Last-In-First-Out (LIFO) demand. The latter category is First-In-First-Out (FIFO) demand. The principle of splitting demand into two categories is valid for supermarkets as well as other settings, see Ishii (1993), Pierskalla (2004), Haijema et al. (2007), Broekmeulen and van Donselaar (2009), and Deniz et al. (2010).

The distribution of the total demand in a basic period has a mean μ and standard deviation σ. FIFO demand is a fraction f of the total demand; hence, using the method of Adan et al. (1995), the FIFO demand distribution is fitted on a mean $f\mu$ and a standard deviation $\sqrt{f}\cdot\sigma$; a LIFO demand distribution is fitted on a mean $(1-f)\mu$ and a standard deviation $\sqrt{(1-f)}\cdot\sigma$. Unsatisfied demand is assumed to be lost at a unit penalty (shortage) cost c_s.

The state of the inventory system at a review point at time t is as follows:

- $(L-1)^+$ outstanding orders $q_{t-1}, \ldots, q_{t-L+1}$. Note, just after replenishment there will be no outstanding orders, if $L \le 1$.
- x_{it} is the number of products (physically present) in stock of $i \in \{0, \ldots, m-1\}$ days age.

For the inventory policies, we use the inventory position IP_t after discarding outdated items before ordering defined as

$$IP_t = \sum_{j=1}^{L-1} q_{t-j} + \sum_{i=0}^{m-1} x_{it}. \tag{1}$$

In the next subsections, we introduce existing and new policies with one to four parameters.