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Perishable inventory management with dynamic pricing using time–temperature indicators linked to automatic detecting devices ☆

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ABSTRACT

We consider the problem of inventory management of perishable products, typical examples of which include food, beverage, and pharmaceuticals. Retailers increasingly use RFID-supported time–temperature-indicator-based automatic devices (TTI-based ADs) to keep track of the age and quality of perishable items in stock and to reduce the risk of selling damaged products to customers. They also apply dynamic pricing to entice consumers to purchase items that approach their expiry dates. The problem is to maximize the retailer's profit while taking customer satisfaction into account. We first formulate the problem as a deterministic non-linear mixed integer program and apply a local search algorithm to approximately solve the problem. We then conduct sensitivity analysis based on extensive simulation experiments to evaluate the impacts of adopting TTI-based ADs and other factors on the solution under different scenarios.

1. Introduction and literature review

We consider the problem of inventory management of perishable products, where safety incidents may occur in case that a quality drop is undetected before expiry date. Typical examples of such products include food, beverage, and pharmaceuticals. It is a common practice that retailers attach a label to each perishable item that denotes its expiry date, or lifetime, after which the item is not proper for its original use.

Considerable research has been done on deteriorating inventory systems and the vast literature has been reviewed by Nahmias (1982), Raafat (1991), Goyal and Giri (2001), Wee and Law (2001), and Li et al. (2010), among others. Nandakumar and Morton (1990), Perry (1997), and Liu and Lian (1999) study fixed lifetime perishable products. Petruzzi and Dada (1999), and Weatherford and Bodily (1992) provide reviews of research on perishable inventory with price-dependent demand. A possible way for retailers to entice customers to purchase a perishable product and eventually increase profits is by offering a price discount that increases when the product approaches its expiry date. This will reduce inventory cost, either by avoiding the need for discarding outdated inventory or of returning the product to the manufacturer. A review of the literature and current practices in dynamic pricing in inventory is carried out by Elmaghraby and Keskinocak (2003). In our paper we refer dynamic pricing to continuous pricing policies where the price trajectory is a decreasing continuous function of time. A few studies have considered such a price differentiation strategy in the context of deteriorating inventory, see, e.g., Smith (1975), Chung et al. (2007), and Roy and Chaudhuri (2007). Since products with little time left to expiry can be utilized for various purposes, the strategy of differentiating price by expiration date can generate additional demand, producing additional profits.

While the price differentiation strategy increases the quantities of products sold and reduces obsolescence, it also increases the probability of selling obsolete or damaged items to customers. Occasionally when unexpected events cause some items to be damaged before they expire, neither the retailer nor the customers are aware of it. Consequently, some customers may have purchased the damaged products. Some of those customers may suffer severe damages such as health problems or safety risks in the course of using the damaged products. The retailer, as a result, loses its reputation and may have to compensate the customers who suffer from the use of damaged products. The compensation expense is usually many times higher than the unit cost of the product.

The emergence of automated identification technology may provide a solution to the above problem. With advanced tracking

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technologies and networked information systems in food supply chains, the information and risk assessment can be available to supply chain partners more readily nowadays (Li et al., 2006b). Such a technology exploits electronic labeling and wireless identification of objects, which facilitates real-time product quality visibility and accurate tracking at all the stages of the product life-cycle (McFarlane et al., 2003; Tauokis and Labuza, 2006). A review of the technical and scientific state of the art of wireless sensor technologies and standards for wireless communications in the Agri-Food sector is given by Garcia et al. (2009). Automatic detecting of spoiled items is required to efficiently support the supply chain. As exact storage conditions are unpredictable, off-line setting of the expiration date is an inaccurate way to inform customers of the quality or safety of a product. In recent years, in the context of inventory management, a technology called time–temperature indicator (TTI) or *smart tag* has been developed. This technology enables retailers to determine on-line the actual quality condition of a product compared with its announced expiry date. In situations where the product is unexpectedly damaged, the TTI-based automatic device (AD) will alert the retailer. The technology reduces the risk of selling damaged products to customers.

TTI-based ADs use chemical reactions to exhibit an irreversible change in the expiry-date label's color in response to the combined effects of time and temperature. A wide array of TTI-based ADs is available on the market, based on different technologies. Simple devices are based on migration of dye through a filter paper, while more complicated ones contain pouches with bacterial fluids that change color when a certain time–temperature combination has been reached. TTI-based ADs are often made as labels. They offer customers better protection and contribute to the environment by reducing the amount of food waste. Most sophisticated TTI labels that combine both chemical and electronic functionality with radio frequency identification (RFID) technology could remotely warn users and automated systems whenever instability problems have occurred. The labeling system may include electronic circuitry that measures, calculates, emits signals of price discount, and eventually reveals that the time has come for disposing of rather than selling a product. Optionally, the circuitry may act as an “over-temperature alarm” system, to measure, calculate, and indicate when a temperature violation has occurred that is of such a magnitude that the item is to be immediately considered damaged or spoiled (McFarlane et al., 2003; Saigin, 2007). Due to the quality deterioration nature of perishable products and due to the health risks involved, end-to-end traceability becomes significant in the agri-food sector (Nambiar, 2009). Several applications of a agri-food supply chain surveillance system based on RFID tags to improving traceability of food health risks are considered by the works of Amador et al. (2009), Yan et al. (2008), Abad et al. (2009), Hsu et al. (2008), Liu et al., (2008), and others.

In this paper we consider the problem of inventory management of perishable products with dynamic pricing using TTI-based ADs. It is complementary to Li et al. (2006a) who propose a model for optimization of product flows in a dynamic forwarding process, which always looks at succeeding process based on current real-time product quality information that is provided by RFID systems. Their model objective is to minimize cost, where one of the objective's components is loss of product value, which is exponentially affected by duration the product is exposed to the measured temperature. Herbon et al. (2012) show through simulations that, with a 0.99 level of confidence, a moderate differentiation of prices in inventory systems increases profits, while a larger differentiation reduces profits. Continuing their study, we consider a retailer that uses an inventory system to manage a single type of perishable product, where all the items in a given shipment arrive periodically on the same date and are assigned the same expiry date. The retailer adopts the price differentiation strategy, i.e., offering a larger price discount for inventory items that are closer to their expiry dates, to jack up customer purchases in order to gain higher profits. As in You (2005), the suggested model assumes for each item a retail price that exponentially declines with the time elapsed from its replenishment. The information about the price and expiration date of any given item is available on-line to potential customers through the RFID. The task of dynamically assigning prices to the items keeps active as long as the items are not removed from inventory due to purchasing, expiry alert, or sudden alert of quality drop.

Since unexpected events may cause inventory items to be damaged before expiration, some damaged goods may inadvertently be sold to customers, compromising performance, sometimes significantly, unless a TTI-based AD is incorporated in the product. Incorporating TTI-based ADs for detecting spoiled items into perishable inventory and modeling such an inventory system is a comparatively new and promising direction for improving service quality. This work aims to fill up a gap in the current literature, which lacks an analysis of customers' utility and other parameters, such cost of the detection technology, and penalty costs within the frame of management of perishable inventory using TTI-based ADs. We first formulate the problem as a nonlinear mixed integer program (NMIP) and apply a local search algorithm to approximately solve the problem. We then conduct extensive simulation experiments to evaluate the impacts of using TTI-based ADs on the obtained solution under different real life scenarios.

This paper is organized as follows. We introduce the problem and the modeling framework in Section 2. Then we formulate the problem as a deterministic NMIP in Section 3. We present a local search algorithm to approximately solve the problem in Section 4, followed by discussion of the simulation experiments in Section 5. We discuss the experimental design and simulation results in Section 6. Finally, Section 7 concludes the paper and suggest topics for future research.

2. Problem statement

We consider a multi-period, capacitated finite-horizon inventory system for a single perishable product with periodic replenishments. Specifically, a retailer periodically replenishes its stock from a supplier and sells the product to customers. As discussed in the Introduction, perishable products typically suffer from quality deterioration over time; however, they still may be sold until their expiry dates. In order to quantitatively evaluate quality deterioration, we adopt the concept of product freshness (measured in time units as the difference between the expiry date and the current time). Along with this characteristic, we assume that the retailer and consumers may obtain more information about quality deterioration with the help of an available TTI-based automatic detection device. Such a device provides real-time information about the current status of every item in inventory, e.g., a sudden drop in quality due to an unforeseen damage to an item. On the occurrence of such an averse event, the retailer needs to remove the damaged item from shelf immediately even when it is far from expiry. This latter information complements the information about product freshness and provides the retailer with a more complete knowledge about whether or not a specific item in inventory is proper for sale. In this context, the additional TTI-based information may improve and increase the consumption of good-quality products and, in the long run, increase the retailer's profit. Consequently, a trade-off between the potential revenue increase, on the one hand, and retailer's expenses for installing a TTI-based