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Joint optimal dynamic pricing and replenishment policies for items with simultaneous quality and physical quantity deterioration

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ABSTRACT

This paper discusses optimal dynamic pricing and replenishment policies for items with simultaneous deterioration of quality and physical quantity. Qualitative deterioration is assumed to be instantaneous, while physical deterioration follows non-instantaneous pattern. In order to tackle dynamic essence of the problem, selling price is defined as a time-dependent function of the initial price and discount rate. The product is sold at the initial price value in the time period with no physical quantity deterioration; subsequently it is exponentially discounted to boost customer's demand. In addition to price, the demand rate is dependent on the quality of inventory and changes in price over time. This consideration has enhanced dynamic characteristic of the proposed model. The model seeks to maximize total profit of the system by determining the optimal replenishment cycle, initial price and discount rate. In order to characterize the optimal solution several theoretical results are derived which demonstrate existence and uniqueness of the optimal solution. Then an iterative solution algorithm is developed based on these theoretical results. Finally, in order to analyze the behavior of model and illustrate the solution procedure numerical results accompanied by sensitivity analyses of key parameters of the model are provided.

1. Introduction

Traditional inventory models take the implicit assumption into account that goods have an infinite life cycle, while this assumption does not hold in reality. The majority of products loses their initial value and undergo deterioration over time [1]. Due to the technological advances, the significance of deterioration has been highlighted. That is because most of the items which were not prone to deterioration in classical view experience shorter life cycles now. Deterioration results in a drop in quality and physical quantity of inventory and subsequently imposes additional costs on the system. Therefore, appropriate inventory control of deteriorating items is a problem of major concern.

Retailers have the choice to compensate for the negative impact of deterioration by implementing different marketing policies that increase the inventory depletion rate. Customer's demand is directly dependent on his level of satisfaction and selling price plays a key role in this regard. So applying appropriate pricing policies enhances the ability of firms in managing

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demand and making profit. Dynamic pricing has been arisen as a powerful pricing policy since it provides retailers with the opportunity to change price over time due to variations in stock-level, demand-level, quality and other influential factors.

Emergence of tracking and monitoring technologies such as Radio Frequency Identification Devices (RFID) and Time-Temperature Indicators (TTI) has provided the opportunity for effective management of inventory [2]. This has made retailers able to consider qualitative and quantitative features of deterioration simultaneously.

Joint pricing and inventory control of deteriorating goods is a rich area of academic research which has been extensively investigated in operations research and revenue management. Jia and Hu [3] studied a two-period life time product in which the demand of each period followed a random price-dependent function. Ghasemy Yaghin et al. [4] studied a similar problem in a bi-level supply chain for a multi-product and multi-period system. Chen and Sapra [5] also investigated a same problem under two inventory scenarios: First-In-First-Out (FIFO) and Last-In-First-Out (LIFO).

Wu et al. [6] introduced non-instantaneous deterioration for the first time which was appropriate for deterioration pattern of many products. Soni and Patel [7] investigated optimal pricing and inventory policies for non-instantaneous deteriorating items with permissible delay in payments. Soni and Patel [8] extended the previous model by considering imprecise deterioration free time and credibility constraint. Shah et al. [9] considered an inventory system with non-instantaneous deteriorating items in which demand rate was a function of selling price and the frequency of advertisement. In addition to these studies, Maihami and Nakhai Kamal Abadi [10,11], Panda et al. [12], Ghoreishi et al. [13] and Zhang et al. [14] incorporated non-instantaneous deterioration into their model.

Cai et al. [15] proposed one of the rare studies on dynamic pricing which modeled price as a function of time. Optimal policy was obtained by considering feedback of price on demand per time unit. Wang et al. [16] also considered price as a function of time. Two static pricing models, including a uniform pricing model and a two-stage pricing model, were carried out to compare with the dynamic pricing model which showed the significant advantage of the dynamic strategy. As another related study, Rabbani et al. [17] modeled price as a function of time and also incorporated the impact of price changes into their demand model to tackle the dynamic nature of the problem.

Herbon et al. [18] investigated usage of time-temperature indicators for inventory management of perishable products. They also applied dynamic pricing to entice consumers to purchase items that approach their expiry dates. As a noble feature of their model, price was considered to decreases exponentially over time.

Soni [19] investigated optimal replenishment policies for deteriorating items with price and stock-sensitive demand under permissible delay in payment. Lu et al. [20] also linked demand to the inventory level. They also embedded replenishment capacity limitation into their inventory system. As one of the very rare studies, Qin et al. [2] considered pricing and lot-sizing problem for products with simultaneous quality and physical quantity deterioration. The demand rate was assumed to be deterministic and dependent on the quality of items, the selling price and the on-display stock-level.

Liu et al. [21] modeled a perishable food inventory system for which, the demand depended on the price and quality of the items. The paper sought to find the optimal price and preservation technology investment of the system. Dye and Yang [22] also tried to optimize price and preservation technology investment in their proposed study. They investigated reference price effects in their model as well.

Soni and Joshi [23] proposed a generalized economic order quantity-based model for deteriorating items under bi-level trade credit financing. Xiao and Xu [24] developed a Stackelberg game model of a bi-level supply chain for deteriorating items which investigated how to coordinate price and service level decisions under vendor-managed inventory system. Chew et al. [25] determined the order quantity and prices of perishable products with a multiple period lifetime. Demands for products of different ages were considered to be dependent on the prices of mutually substitutable products. Li et al. [26] studied the joint dynamic pricing and inventory control policy for a stochastic inventory system with perishable products. They applied the stochastic optimal control method to formulate the problem.

Although pricing and inventory control of deteriorating items is a widespread research topic, there still exist several gaps in body of the literature. In the context of dynamic pricing, most of the papers considered multi-period pricing as dynamic pricing and there exist very few papers that modeled price as a time-dependent function. To the best of our knowledge, none of the studies incorporated the effect of changes in price into the demand function. This consideration enhances dynamic feature of the problem. Finally, there is only one paper which modeled quality and physical quantity deterioration simultaneously, while this consideration does hold in reality and there is usually a direct link between quality of an item and its demand.

Inspired by the significance of the problem and related research gaps, this paper provides an integrated approach for dynamic pricing and inventory control of products with simultaneous quality and quantity deterioration. The quality of product starts to deteriorate over time instantaneously. This reduction of quality level does not affect the physical quantity for a while. After a specific point of time, goods start to lose their utility due to quality drops and subsequently non-instantaneous quantity deterioration starts. To reflect dynamic nature of the problem, not only selling price is modeled as a time-dependent function of the initial price and discount rate but also the effect of changes on price is incorporated into the demand model. In addition to dynamic price and changes in price, demand rate is dependent on quality of inventory as well. Since quality of inventory deteriorates over time, applying time-dependent inventory holding cost makes us able to maintain freshness of items as long as possible. Modeling the deterioration rate as time-dependent functions has raised the practicality of the proposed framework as well.

The remainder of the paper is structured as follows. In Section 2, notations and assumptions of the problem are described. Section 3 represents the formulated mathematical model. Section 4 provides the theoretical results and the