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# A mathematical model for perishable products with price- and displayed-stock-dependent demand

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A B S T R A C T

We introduce an economic order quantity model that incorporates product assortment, pricing and space-allocation decisions for a group of perishable products. The goal is to maximize the retailer's profit under shelf-space and backroom storage capacity constraints. We assume that the demand rate of a product is a function of the selling prices and the displayed stock levels of all the products in the assortment. We propose a Tabu Search based heuristic method to solve this complex problem.



## 1. Introduction

Walking into any grocery store, it may be striking to come across a salad-dressing aisle filled with dozens of varieties spread across two dozen brands, or to figure out what kind of Oreo brand cookie to choose among nearly 50 different versions of its classic cookie, or to stand in front of a Pantene hair-care aisle and decide on buying one of the 88 kinds of Pantene shampoo, conditioner and styling products. Apparently, nowadays, supermarkets are packing their shelves with an ever-expanding array of products in different brands, sizes, colors, flavors and prices. According to survey data from the Food Marketing Institute, nearly 47,000 distinct products filled a typical supermarket retailer's shelves by 2008, up more than 50% from 1996.[1] Likewise, *New Product News* reports that in the food category alone, 1677 new products were introduced in 2001 by the 20 largest food companies in the U.S., which was the highest figure since the mid-1990s. The fact is, companies are overwhelmingly following the 'more is better' route and increasing the number of alternatives they offer within their brands. In today's strategic landscape, a broader portfolio of products often can help a company capture more value as it increases not only the chances of appealing to a wider variety of customers but also the number of other products that can benefit from a hit product's popularity. The yellow flag here is that a broader product portfolio usually heightens three strategic challenges facing managers: management of scarce retail display areas/shelf-space, inventory management, and pricing. Recently, the number of new products offered to the supermarkets has grown at too fast a pace compared to the increase in the average size of a store and in the amount of shelf-space available. *USDA's Economic Research Service estimates the number of packaged food products available to American consumers to be about 320,000. However, a typical supermarket can accommodate only 50,000 products, including non-food items.*[2] This points to a constant battle between different products for the limited shelf space in stores - adding variety in a product category and allocating a larger shelf space to it can result in trimming variety and space for other products.

The proliferation of products competing for limited shelf spaces necessitates retailers to scrutinize their shelf space management strategies, at the heart of which lies the major concern for determining the appropriate amount of inventory displayed. For particular product categories, consumer demand increases when stores maintain higher inventory levels. Balakrishnan, Pangburn, and Stavrulaki (2004) suggest that tall stacks of an item can increase

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[1] http://www.gpnmag.com/something%E2%80%99s-happening-here-0, accessed September 19, 2012.

[2] http://www.ers.usda.gov/publications/foodreview/sep1997/sept97g.pdf, accessed June 16, 2011.

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sales for various reasons such as "increasing product visibility, kindling latent demand, signaling a popular product, or providing consumers an assurance of future availability." This demand stimulation factor particularly applies to impulse purchase of novelty items (e.g., fashion items, magazines, and consumer electronics products) that can be displayed effectively. The facings or display spaces let them be more visible, and the visibility in turn creates additional demand. This promotional role of inventory is often described by retail managers as the "stack them high, let them fly" phenomenon.

In a competitive market, prices of goods is another factor that affects the decision making process of a customer. Generally, a reduced price encourages a customer to buy more. Both the price and the shelf space allocated for an item are important factors that determine the demand of that item. Therefore, besides determining shelf spaces for the items, the retail managers should also determine the prices of the items. What is more interesting is that the demand of a particular product might also be affected by the prices and the spaces allocated for the other products on the shelves. That is, there might be cross dependencies between products on the shelves. Urban (1969) notes that interdependencies among the brands of a firm's product line should be considered when making marketing strategies. This implies that the retail managers should not only determine the prices and the display areas allocated to the stocked units, they should also determine which brands and/or products should be displayed together on the shelves to maximize their overall profits. The problem of determining the optimum portfolio of brands and/or products to get the best use of available shelves is called the product assortment problem.

The product assortment, pricing and shelf allocation decisions are particularly important when the items are perishable, because (i) it is more desirable to have higher demand rates for perishable items (in order to sell as much as possible in their short shelf lives) and (ii) due to their certain storage requirements (e.g., low temperature and humidity, bookkeeping to ensure on-time replenishments) the shelf spaces are limited for those items.

Deteriorating items are usually classified with respect to how their utilities change in time. Some items deteriorate continuously over time, where the deterioration rate is usually proportional to the amount of available inventory (see Goyal and Giri (2001) and Bakker, Riezebos, and Teunter (2012)). Some items have certain lifetimes after which they deteriorate completely. These items are said to deteriorate instantaneously (see Urban (2005) and Bakker et al. (2012)). For continuously deteriorating items, deterioration increases the depletion rate of the items in the stock. Since the demand is affected by the inventory level, deterioration affects instantaneous the demand rate of the item. On the other hand, for instantaneously deteriorating items (i.e., items with predetermined shelf lives), shelf life restrictions force the retailers to keep fewer number of items in stocks, although the retailer has a tendency to keep high levels of inventory to stimulate demand.

These observations motivate the focus of this paper. We establish a product assortment model in which items are perishable and the demand rates of the items depend on the displayed stock levels and the selling prices of the items in the assortment list. To the best of our knowledge, no study has yet integrated a perishable inventory model with assortment, pricing and shelf-space allocation decisions. In our model, we assume that items have predetermined shelf lives after which they must be discarded. We assume that items are of constant value to the consumer as long as they don't expire. Some examples are prescription drugs, pharmaceuticals (e.g., vitamins, cosmetics), chemicals (e.g., household cleaning products), batteries, photographic films, and frozen food. These products have a fixed shelf life, and they undergo decay but face no appreciable decrease in value during their usable lifetime. This also includes product categories that undergo unobservable change in storage so that they may become obsolete but offer non-decaying utility.

The remainder of the paper is organized as follows. Section 2 presents some related literature on inventory models that incorporate effects of displayed stock levels, prices and perishability. We define our product assortment problem, list our notation and assumptions in Section 3. We present a mathematical formulation of the problem in Section 4. In Section 5 we propose a metaheuristic solution approach to this problem. The numerical results and some managerial insights are reported in Section 6. Section 7 concludes the paper with a discussion of the main results and potential extensions of the model.

## 2. Literature review

A considerable amount of research has been done on inventory control policies assuming that demand is affected by the amount of available inventory. This research area has been extended in several ways by incorporating pricing, perishability and assortment decisions.

Empirical evidence on the dependence of demand on inventory of certain products has been provided by Larson and DeMarais (1990), who refer to inventory that stimulates demand as "psychic" stock, and more recently by Koschat (2008). In particular, Koschat (2008) presents empirical evidence that demand can indeed vary with inventory by investigating a major US magazine publisher, and quantifies the magnitude of the dependence of demand of a brand on its own inventory as well as the inventory of a substitutable magazine brand. In addition to these empirical papers, a number of theoretical models have been developed to determine the appropriate inventory policy with the impact of inventory on sales. Gupta and Vrat (1986) introduced the notion of endogenous, inventory-dependent, deterministic demand as a function of the initial stock level. Later on, Baker and Urban (1988) developed an inventory model where the demand rate depends not on the initial, but on the instantaneous inventory level throughout sales. In their model, they assumed that the zero-inventory-order (ZIO) property holds, that is, new items are not ordered unless the items in stocks are consumed completely. Urban (1992) improved this model by relaxing the ZIO property. Recently, Alfares (2007) has proposed an inventory model with stock-level dependent demand rate and variable holding cost, and Soni and Shah (2008) has formulated optimal ordering policies when demand is partially constant and partially dependent on the stock. More recent examples on inventory models with inventory dependent-demand include, Pando, García-Laguna, and San-José (2012), which assumes nonlinear holding costs; and Alfares (2015), which assumes finite production rates.

Some researchers focused their attention on the inventory models that coordinate pricing decisions with stock-dependent demand. Urban and Baker (1997) generalized the EOQ model by formulating the demand as a multivariate function of price, time and inventory level. Datta and Paul (2001) and You and Hsieh (2007) analyzed multi-period models with stock-dependent and price-sensitive demand rate.

There is also a huge stream of research that incorporates perishability into EOQ models with inventory dependent demand. Earlier examples include Padmanabhan and Vrat (1990),Giri, Pal, and Chaudhuri (1996), Hwang and Hahn (2000), Zhou and Yang (2003), and Dye and Ouyang (2005). Teng and Chang (2005) established an economic production quantity model with finite production rate, and Chang, Chen, Tsai, and Wu (2010) proposed an EOQ model, for continuously deteriorating items, where the demand rate depends on the selling price and the displayed stock level of the item. Wu, Ouyang, and Yang (2006) considered a replenishment