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Integrated retail decisions with multiple selling periods and customer segments: Optimization and insights ☆

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ABSTRACT

Integrating retail decisions on such aspects as assortment, pricing, and inventory greatly improves profitability. We examine a multi-period selling horizon where a retailer jointly optimizes assortment planning, pricing, and inventory decisions for a product line of substitutable products, in a market with multiple customer segments. Focusing on fast-moving retail products, the problem is modeled as a mixed-integer nonlinear program where demand is driven by exogenous consumer reservation prices and endogenous assortment and pricing decisions. A mixed-integer linear reformulation is developed, which enables an exact solution to large problem instances (with up to a hundred products) in manageable times. Empirical evidence is provided in support of a classical deterministic maximum-surplus consumer choice model. Computational results and managerial insights are discussed. We find that the optimal assortment and pricing decisions do not exhibit a simple, intuitive structure that could be analytically characterized, which reflects the usefulness of optimization approaches to numerically identify attractive trade-offs for the decision-maker. We also observe that suboptimal inventory policies significantly decrease profitability, which highlights the importance of integrated decision-making. Finally, we find that the seasonality of consumer preferences and supply costs present an opportunity for boosting the profit via higher inventory levels and wider assortments.

1. Introduction and motivation

The post-industrial era has seen the rise of service industries coupled with technological developments and innovative management practices. In particular, the retail industry has witnessed the emergence of giant retailers such as Walmart, Amazon, and others. Concurrently, a large body of literature grounded in mathematical and statistical methods was produced to enable retail analytics. The extent of the studies in this fertile arena and the sophistication of the proposed tools is indicative of what Fisher et al. [10] coined as "rocket science retailing." Given the flux and change in the retail industry, the managerial decisions that arise in the design of value chains, the planning of production and logistics, and the control of levers that govern the market are now critical. The vitality of this research area is underscored by the fact that the retail industry, one of largest employer worldwide, is under financial pressure. For example, the net profit margin after tax in the US grocery industry was only 1.09% in 2011 [11].

In a competitive market with demanding consumers, there exists a pressing need in the retail industry for decision support tools that reflect emerging industry practices [20] and integrate key decisions cutting across several departments (e.g., marketing and operations). Such planning and policy identification must align with the ever-changing customers' preferences and taste, and simultaneously ensure the financial viability and profitability of the business. This paper addresses the development of tactical optimization models (mixed-integer nonlinear/linear programs) for assortment planning, pricing strategies, and inventory management policies for the design and control of retail product lines. Specifically, we consider product lines of substitutable products that fulfill the same customer need, but commonly differ by secondary attributes (e.g., different brands of soda or coffee). We henceforth consider the setting where a retailer simultaneously seeks to select a subset of products (an assortment) to offer in a product line over a multi-period selling horizon and to determine the optimal prices and inventory levels for the composed assortment in each time-period. In this context, it is imperative to identify policies that are cognizant of time-varying supply costs and seasonal changes in customer preferences.

In practice, several retailers are advocating the use of integrated pricing/assortment/inventory decision frameworks. For example, a JCPenney executive reports that "assortments, allocations, markdown

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pricing are all linked and optimized together" at his company [12]. Likewise, a Saks Department Stores executive indicates that for assortment planning, his company analyzes information on sales, inventory levels and store performance [6]. Moreover, it is reported that at Saks the integrated assortment and stock levels solution is adjusted on a weekly basis "to accommodate trends, seasons and promotions," which is in-line with the multi-period setting that we propose. The academic literature has responded to this growing interest in integrated retail decision-making through several studies that jointly consider key decisions on assortment, pricing, and inventory (as detailed in the recent survey by [33]). By design, most studies consider stylized (single-period) models that are aimed at deriving analytical results and revealing certain managerial insights under specific assumptions. Although valuable, such analytical results do not address the retailer's immediate need for a data-driven decision-support framework that can accommodate large-scale product lines that may comprise hundreds of products over a multi-period planning horizon. In this paper, we develop an optimization approach that caters for large-scale retail problems and reveals trade-offs involved in integrated decision-making under procurement- and consumer-driven data.

Our model is developed with the idea that demand over the multi-period selling horizon is generated by aggregating consumer preferences which are based on the retailer's prices and reservation prices estimated deterministically for several customer segments with known sizes. Such a demand model is common in the marketing literature (see, e.g., [7,8] and references therein). The cost structure conforms to the classic dynamic lot-sizing model and includes inventory holding costs and fixed and variable ordering costs, as well as an additional fixed cost for offering an item in the assortment at the beginning of the selling season.

The resulting model involves deterministic demand patterns for the offered products, which are driven by pricing and assortment decisions under consumer choice. Such demand patterns are observed in a wide class of retail products. Of particular interest to our study are long lifecycle fast-moving consumer goods (FMCG) such as office supplies, canned groceries, or health and beauty products with predictable demand patterns and responsive supply sources. For instance, Sarnevitz [39] describes SAS' decision framework for FMCG in their proposed retail analytics software, which utilizes deterministic demand forecasts. It is interesting to note here that SAS' proposed framework for FMCG also involves the integration of pricing, assortment, and allocations (inventory). It is also worth noting that the insights developed in the present paper, summarized below, illustrate how complex trade-offs govern retail decisions over multiple selling periods and costumer segments and can serve as a useful benchmark for future studies on integrated assortment, pricing, and ordering under stochastic demand models (such as in fashion retailing).

The paper makes the following contributions. First, on the computational front, we develop a multi-period mixed-integer nonlinear program (MINLP) that offers an integrated framework for jointly optimizing assortment, pricing, and inventory decisions. Although, in our experience, this MINLP model is not computationally tractable even for small-sized instances using global solvers such as LINGO Global Solver, we propose a model linearization that results in a computationally attractive exact solution method (using CPLEX 12.4) for large problem instances with up to a hundred substitutable products.

Second, we discuss the following managerial insights through our computational study.

(i) The optimal assortment and prices do not have a simple structure that can be intuitively characterized. For instance, the optimal assortment cannot be constructed by an "average margin" metric, as common in stylized retail models (e.g., [33]). This is primarily due to seasonality in demand and cost. In addition, the optimal price of a product does not necessarily equal one of the consumer reservation prices, as one may expect with a deterministic consumer choice model. This is due to cannibalization effects between the different customer segments.

(ii) Naive (myopic) inventory policies significantly decrease profitability, which highlights the importance of integrating ordering with pricing and assortment decisions. In particular, we observe that adopting a variant of economic order quantity policy (that we refer to as a zero-inventory policy, or ZIP) leads to a profit reduction that can reach 70% in our testbed, and significantly distort the structure of an optimal assortment.

(iii) Predictable seasonality of demand and cost is beneficial, and can lead to significant increase in profitability if the retailer stocks wider assortments and higher shelf inventories. For example, we observe that seasonality can boost profit by up to 40% in our testbed. Wider assortments cater for the fluctuating consumer needs, and higher inventory levels reflect the effect of "stocking-up" when the merchandising costs drop.

The remainder of this paper is organized as follows. Section 2 provides a literature review of works in retail management that investigate assortment, pricing, and inventory decisions for substitutable products. Thereafter, a formal problem statement is presented in Section 3 along with a multi-period mixed-integer nonlinear model for which a linear reformulation is developed. Section 4 demonstrates the applicability of our demand model based on real data for a Tuna category. To illustrate how our model can be empirically calibrated, we fit the parameters of the demand model (e.g., the reservation prices) to this Tuna data. Section 5 presents our computational study along with relevant managerial insights in order to demonstrate the usefulness of the proposed integrated model and the efficacy of our exact solution methodology for relatively large problem instances. Section 6 discusses possible refinements of the consumer choice model whereby the fraction of a customer segment that purchases a product that maximizes its surplus is a non-increasing function of product prices. Section 7 summarizes our findings and highlights directions for future research.

2. Literature review

This paper is mostly related to recent works that investigate the integration of assortment, pricing, and inventory decisions, or a subset of these decisions, for retail product lines composed of substitutable items. This section provides a brief literature review, and the more inquisitive reader is referred to the survey by Maddah et al. [33]. In Section 2.1, we review the works that utilize mathematical programming in the aforementioned retailing decisions contexts. Our work relates mostly to this stream of literature. Then, in Section 2.2, we review works that utilize stylized models to gain insights into the optimal structure of these decisions. Finally, in Section 2.3, we review background literature from marketing and operations management, focusing on the methods utilized in marketing to estimate the consumer reservation prices, which are key inputs to our optimization model.

2.1. Mathematical programming approaches

Our work is primarily related to studies that are grounded in optimization models and mathematical programming approaches for data-driven, large-scale retail problems. Most studies consider, under different assumptions, at most two of the three decision variables that are integrated in this paper, namely, assortment, pricing, and inventory decisions. For example, Yücel et al. [45]