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Review

Dynamic pricing and learning: Historical origins, current research, and new directions

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HIGHLIGHTS

- The historical origins of research on pricing and demand estimation are sketched.
- An in-depth survey of literature on dynamic pricing and learning is given.
- Relations with methodologically related research areas are highlighted.
- Important directions for future research are identified.

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ABSTRACT

The topic of dynamic pricing and learning has received a considerable amount of attention in recent years, from different scientific communities. We survey these literature streams: we provide a brief introduction to the historical origins of quantitative research on pricing and demand estimation, point to different subfields in the area of dynamic pricing, and provide an in-depth overview of the available literature on dynamic pricing and learning. Our focus is on the operations research and management science literature, but we also discuss relevant contributions from marketing, economics, econometrics, and computer science. We discuss relations with methodologically related research areas, and identify directions for future research.

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Pricing is an interesting problem from Economics.[1]

1. Introduction

Dynamic pricing is the study of determining optimal selling prices of products or services, in a setting where prices can easily and frequently be adjusted. This applies to vendors selling their products via Internet, or to brick-and-mortar stores that make use of digital price tags. In both cases, digital technology has made it possible to continuously adjust prices to changing circumstances, without any costs or efforts. Dynamic pricing techniques are nowadays widely used in various businesses, and in some cases considered to be an indispensable part of pricing policies.

Digital sales environments generally provide firms with an abundance of sales data. This data may contain important insights on consumer behavior, in particular on how consumers respond to different selling prices. Exploiting the knowledge contained in the data and applying this to dynamic pricing policies may provide key competitive advantages, and knowledge how this should be done is of highly practical relevance and theoretical interest. This consideration is a main driver of research on *dynamic pricing and learning*: the study of optimal dynamic pricing in an uncertain environment where characteristics of consumer behavior can be learned from accumulating sales data.

The literature on dynamic pricing and learning has grown fast in recent years, with contributions from different scientific communities: operations research and management science (OR/MS), marketing, computer science, and economics/econometrics. This survey aims at bringing together the literature from these different fields, and at highlighting some of the older (and sometimes forgotten) literature where many important results and ideas already can be found.

A few literature reviews on dynamic pricing and learning do already exist. Araman and Caldentey [2] and Aviv and Vulcano [3, Section 4] review in detail a number of recent studies, mostly from the OR/MS community; Christ [4, Section 3.2.1] contains an elaborate discussion of a selection of demand learning studies; and Chen and Chen [5] review recent research on multiple-product pricing, pricing with competition, and pricing with limited demand information. Our survey complements these publications by aiming at a larger scope, and, although our main focus is on the OR/MS literature, we also address relevant contributions from computer science, marketing, economics and econometrics.

Content. This survey reviews the literature on dynamic pricing with demand uncertainty. We discuss how this is embedded in the literature on dynamic pricing in general, but do not review all relevant research topics associated with dynamic pricing; for this we refer to Bitran and Caldentey [6], Elmaghraby and Keskinocak [7], Talluri and van Ryzin [8], Phillips [9], Heching and Leung [10], Gönsch et al. [11], Rao [12], Chenavaz et al. [13], Deksnyte and Lydeka [14] and Özer and Phillips [15]. We focus on studies where selling price is a control variable; we only scarcely discuss learning in capacity-based revenue management [8] or learning in newsvendor/inventory control problems. Neither do we consider mechanism design [16,17] or auction theory with incomplete information (see e.g. [18,19] and the references therein), although there are some similarities with dynamic pricing and learning. Most of the studies that we discuss are written from an (online) retailer perspective; we do not consider social welfare optimization [20,21]. We do not dive into specific details associated with particular application area such as pricing in queueing or telecommunication environments [22], road pricing [23–25], or electricity pricing [26,27], to name a few. We also neglect a recent stream of *empirical* studies that aims to explain the dynamic pricing strategies of sellers by fitting models to sales data (see e.g. [28] for an example on prices of airline tickets, Sweeting [29] on prices of Major League Baseball tickets, and Huang et al. [30] on pricing for a used-car dealership). Finally, this survey focuses on studies where the *seller* learns about the *demand function*, and not on studies where *buyers* (or sellers) learn (typically about the quality of the product) [31–37].

Methodology. We used Google Scholar to find all relevant references that were available online October 1, 2014. We excluded double versions of the same papers, or conference papers that largely overlap with journal papers. For all papers that we found this way we looked on Google Scholar for relevant other work citing these papers. We also checked the websites of key authors in the field for relevant publications. We aimed for a comprehensive review of the dynamic-pricing-and-learning literature; for the other sections, on e.g. demand estimation or dynamic pricing under full information, we restrict to key papers and reviews.

Organization of the paper. This survey is organized as follows. We review in Section 2 some of the pioneering historical work on pricing and demand estimation, and discuss how this work initially was difficult to apply in practice. In Section 3 we sketch important references and developments for dynamic pricing in general, and in Section 4 we focus on the literature that specifically deals with dynamic pricing and learning. Connections between dynamic pricing and learning and related research areas are addressed in Section 5, and related new research directions are discussed in Section 6. The core of the paper is Section 4, while the other sections are supporting.

[1] Zhang et al. [1].