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Joint dynamic pricing and capacity control for hotels and rentals with advanced demand information

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ABSTRACT

This paper studies joint dynamic pricing and capacity control for hotel and rental operations when advanced demand information (ADI) is available for some but not all customers. Dynamic pricing for non-ADI customers and capacity control for ADI customers are jointly considered with a stochastic dynamic programming model. We examine structural properties and fully characterize optimal policies. Based on monotone properties of optimal policies, we develop effective pricing and rationing heuristics, and investigate the value of demand information through numerical studies.

1. Introduction

As a popular practice of matching supply with demand, capacity control (see [15] and [20]) and dynamic pricing (see [5,7,8]) are widely used in revenue management (RM) when selling perishable products such as airline seats (see [12]), hotel rooms (see [4]) and car rental services (see [17]). Hotel groups such as Marriott and Intercontinental replaced fixed consortia rates with dynamic pricing in the early 2000s, when Hilton used dynamic "best available rates" as an alternative to fixed negotiated rates for its corporate accounts too (see [19]). China Auto Rental (CAR), the largest car rental company in China, gained substantial competitive advantage through its excellent dynamic pricing and capacity control operations (according to a report by Credit Suisse, 2014).

Different from the airline industry, two complicated issues arise when applying RM to hotel or rental services. First is the stochastic property of available capacity due to the uncertainty in capacity occupation duration of customers. This is in sharp contrast to airlines, where the duration of occupying a seat in a particular flight is predetermined almost surely. The random arrival of customers and the uncertain length-of-stay/length-of-rental (LOS/LOR) have jointly posed a great challenge to revenue management. The second issue is the presence of different types of customers, including customers providing advanced demand information (*ADI customers*) through reservations vis-à-vis random walk-in customers (*non-ADI customers*) to demand service immediately. Many ADI customers are from contracted companies with certain service obligations, whereas non-ADI customers are often leisure customers "shopping for price" [9]. The rates for ADI customers are considered to be pre-negotiated and fixed with an admission control through capacity rationing, whereas rates for non-ADI customers are controlled through dynamic pricing.

Clearly, with additional information of future demand collected through ADI customers' reservations, a better match between demand and available capacity may be achieved. However, customers may provide only estimates of the due dates when making reservations. The realized due dates may differ significantly from the initial estimates since customers may either extend their duration or cancel some of the reservation days before the due date. To represent such industry reality, a random demand lead time is used to capture the duration extension whereas possible cancelation of ADI customers is modeled through the show-up probability. Moreover, to allow for heterogeneity among ADI customers, we consider multiple classes of customers, each of which has different demand lead time and show-up probability. Apparently, these heterogeneous customers generate different revenues to the firm and incur different penalties (e.g., loss of goodwill) for rejected services.

We study the joint decisions of dynamic pricing for non-ADI customers and capacity control for ADI customers, a common scenario in the hotel and rental service industries. The advanced demand information is imperfect in the sense that demand lead time is random and on-hand reservations may be canceled. Many

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important decisions need to be made in such a framework. What is the optimal strategy of capacity rationing for ADI customers? What is the optimal price the firm should charge for non-ADI customers? How will the lead time and show-up probability affect the pricing decision? How should the two control policies be jointly determined to enhance the total revenue? What is the value of advanced demand information? To address these questions, we formulate the problem as a multi-server loss system (see examples of [16,17]) through continuous-time infinite-horizon Markov Decision Processes (MDP), where both the arrivals of customers and the capacity occupation durations are stochastic under imperfect ADI.

Our findings and contributions are multi-fold. First, we characterize the optimal capacity rationing strategy as a state-dependent multi-level threshold, which is non-increasing in the number of ADI reservations, the number of customers in service, the ADI demand lead time and show-up probability. Reverse monotonicity can be obtained for the optimal price for non-ADI customers. The optimal price is always greater than the myopic price which ignores the opportunity cost of capacity. Second, we show that the value of ADI is most significant when the ADI demand lead time is neither too short nor too long, which is different from the finding of [16] obtained with a deterministic demand lead time. Third, the heuristics developed in this study allow us to identify effective control policies. Specifically, when the willingness-to-pay of non-ADI customers is relatively low, like in non-holidays, it is effective not to ration capacity for ADI customers and set price for non-ADI customers by multiplying the myopic price by a simple load-dependent factor. When the willingness-to-pay of non-ADI customers is relatively high, like in holidays, it is effective to use a one-dimensional and load-dependent linear threshold to ration capacity for ADI customers, and use the same price strategy for non-ADI customers.

Our paper is closely related to two streams of literature on capacity rationing and dynamic pricing for stochastic service/production systems, when the two decisions may be made independently or jointly and advanced demand information may or may not be available. The first stream is on capacity rationing of rentals (see [16,17]) or hotels (see [3,4]) with ADI or without ADI. Different from [17] without ADI and [16] with deterministic advanced demand lead time, we consider the case of stochastic lead time and characterize the structure of the optimal strategies. The studies of [4] and [3] analyze the hotel room rationing policy for single night stay with reservations and develop heuristics for multiple nights through deterministic linear programming (DLP). Different from the standard hotel RM model which adopts DLP based bid-price control heuristics for given LOS, we study the optimal control policies for random LOS of multiple classes with imperfect ADI, focusing on investigating structural properties and the value of ADI to gain managerial insights. In addition, most studies of this stream did not integrate capacity rationing with dynamic pricing under ADI. The second stream focuses on dynamic pricing for perishable products (see [7] and [8]) or production/queueing systems for multiple types of customers without ADI (see [1] and [6]). [9] studies a similar problem like ours on joint capacity control and dynamic pricing, but ADI is not considered. Our work is also closely related to the studies of manufacturing and production system with ADI (see [10,11] and [2]). Different from the hotel or rental service system in our study, there is no uncertain duration of the customer (or product) in the inventory system. Our model integrates ADI with capacity rationing and dynamic pricing in a setting of stochastic system with both random customer arrivals and random resource occupation duration. Our paper is motivated by real industry practices in the hotel and rental service sectors, allowing our study to provide some fresh insights.

The remainder of this paper is organized as follows. Section 2 introduces the model and analytical results. Section 3 reports numerical studies and heuristics. Concluding remarks are provided in the last section. All the analytical proofs are provided in our online supplementary material (see Appendix A).

2. Model

2.1. Model formulation

We consider a hotel or a rental company with c rooms or cars. The firm serves two types of customers, namely ADI customers and non-ADI customers. ADI customers make a reservation in advance and pay the pre-negotiated price when they show up for service. ADI customers are classified into n classes according to the demand lead time and show-up probability. The lead time of class-i ($i = 1, \ldots, n$) ADI customer is assumed to be exponentially distributed with mean $1/\nu_i$ and the show-up probability is q_i. All ADI reservations are accepted until the accumulated volume reaches the upper limit level m_i for class-i which is pre-set by the company. When a class-i ADI demand is due (i.e., when a class-i ADI customer with a reservation shows up), the firm should decide whether to fill the demand (and earn a lump-sum revenue r_i) or to reject the demand (by paying a lump-sum penalty π_i). Note that we adopt lump-sum revenue in our formulation, which can be transformed to an equivalent unit-time revenue by adopting the similar approach as [17] and [9].

Non-ADI customers and class-i ADI reservations arrive according to a Poisson process with rate λ_0 and λ_i, respectively. The company adopts dynamic pricing for non-ADI customers who walk in without prior booking and request the service immediately. Non-ADI customers have a willingness-to-pay with the cumulative distribution function $F(\cdot)$. The company can influence or adjust demand by changing the spot price p, $p \in \mathcal{P} = (0, p_\infty)$, where p_∞ is a null price for which $\lim_{p\to p_\infty} \bar{F}(p) = 0$ (see [7] and [8]), where $\bar{F}(p) = 1 - F(p)$. Therefore, the expected demand rate of non-ADI customers at price p is $\lambda_0\bar{F}(p)$, and the probability of no demand realized is $\lambda_0 F(p)$. The capacity occupation duration is exponentially distributed with mean of μ^{-1} (average LOS/LOR).

Let $v(x, \mathbf{y})$ be the optimal expected total discounted revenue over the infinite horizon, given x customers in service and $\mathbf{y} = (y_1, \ldots, y_n)$ ADI reservations on hand. Using the standard uniformization method (see [14] and [18]), let the uniform rate $\gamma = \lambda_0 + \sum_{i=1}^n \lambda_i + \sum_{i=1}^n m_i\nu_i + c\mu$ and, without loss of generality, $\alpha + \gamma = 1$ where α is the discount rate. The optimality equation is given by

$$
\begin{aligned}
v(x, \mathbf{y}) &= \sum_{i=1}^{n}\Big[\lambda_i T_i v(x, \mathbf{y}) + \nu_i y_i\big(q_i H_i v(x, \mathbf{y}) + (1 - q_i)v(x, \mathbf{y} - \mathbf{e}_i)\big) \\
&\quad + \nu_i(m_i - y_i)v(x, \mathbf{y})\Big] \\
&\quad + \lambda_0 T_0 v(x, \mathbf{y}) + \mu x v(x - 1, \mathbf{y}) + \mu(c - x)v(x, \mathbf{y}), \qquad (1)
\end{aligned}
$$

where

$$
T_0 v(x, \mathbf{y}) = \max_{p\in\mathcal{P}} \left\{\bar{F}(p)\big(v(x + 1, \mathbf{y}) + p\big) + F(p)v(x, \mathbf{y})\right\} \qquad (2)
$$

$$
T_i v(x, \mathbf{y}) = \begin{cases} v(x, \mathbf{y} + \mathbf{e}_i), & \text{if } y_i < m_i, \\ v(x, \mathbf{y}), & \text{if } y_i = m_i, \end{cases} \qquad (3)
$$

$$
H_i v(x, \mathbf{y}) = \begin{cases} \max\{v(x + 1, \mathbf{y} - \mathbf{e}_i) + r_i,\ v(x, \mathbf{y} - \mathbf{e}_i) - \pi_i\}, \\ \quad \text{if } x < c, \\ v(x, \mathbf{y} - \mathbf{e}_i) - \pi_i, \\ \quad \text{if } x = c, \end{cases} \qquad (4)
$$

and $p^* = p_\infty$ when $x = c$; $v(x - 1, \mathbf{y}) = 0$ when $x = 0$; $v(x, \mathbf{y} - \mathbf{e}_i) = 0$ when $y_i = 0$, $i = 1, \ldots, n$. The operator $T_0 v(x, \mathbf{y})$