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Optimal pricing and seat allocation for a two-cabin airline revenue management problem

George J. Kyparisis *, Christos Koulamas

Department of Information Systems and Business Analytics, College of Business, Florida International University, Miami, FL 33199, USA

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ABSTRACT

We consider the single-flight leg two-cabin airline revenue management problem in which there is a flexible partition of the business and economy cabins and determine the optimal cabin partition and the optimal fares for both cabins with both a general and an isoelastic multiplicative price-demand function and three different random demand distributions. We conclude numerically that the optimal partitioning and the optimal pricing is not sensitive to the random demand distributions and that our findings are comparable for two different aircraft types. We also consider the similar problem with a capacity constraint on business and conclude that this constraint drives business class fares up and total revenue down (compared to the unconstrained problem).

1. Introduction

We study a combined allocation/pricing model with applications to a single-airline, single-flight leg revenue management problem in which there is a fixed number of airplane seats to be sold to two classes of customers (economy and business respectively) at different fares.

A related problem is the single-flight leg, single-cabin airline revenue management problem in which an airline must decide the number of economy seats set aside for last minute economy customers who are willing to pay a premium to fly on short notice. In this paper, we consider a different version of the problem motivated by the cabin configuration of several European airlines (eg., British Airways, Aegean Airlines, among others) for short-range flights. These airlines utilize a movable partition to separate their business and economy cabins which are otherwise similar with respect to seat pitch; a row of seats are sold as business class seats by simply blocking the middle seat in each row and positioning the movable cabin partition accordingly. In the sequel, we call this problem the TCARM (Two Cabin Airline Revenue Management) problem.

The objective of this paper is two-fold. We first determine simultaneously the optimal cabin partition and the optimal fares for both cabins. We then compare the expected revenue and optimal fare policies with the corresponding quantities for the similar problem in which the number business class seats is predetermined and fixed to assess the percentage decrease in revenue because of the constraint on the business cabin size. In the latter problem, excessive demand for business class seats is lost while excessive demand for economy seats can be accommodated by issuing free upgrades provided there is unsold capacity in business class.

We conclude numerically that the optimal partitioning and the optimal pricing is not sensitive to the random demand distribution and that our findings are comparable for two different aircraft types. We also consider the similar problem with a constraint on the business cabin size and conclude that this constraint drives business fares up and total revenue down (compared to the unconstrained problem).

There is a large body of literature on revenue management problems and in particular airline yield management problems. Revenue management problems have been reviewed by Weatherford and Bodily (1992) and McGill and Van Ryzin (1999) while Bitran and Caldentey (2003) reviewed pricing models in revenue management. Airline yield management problems have been reviewed by Belobaba (1987); relevant papers in this area include Brumelle et al. (1990), Netessine and Shumsky (2005) and Cizaire and Belobaba (2013). Additional related models with applications to airline revenue management have been proposed by McCardle et al. (2004), Mookherjee and Friesz (2008) and Zhao et al. (2017).

Weatherford and Bodily (1992) proposed a taxonomy for revenue management research which included the areas of yield management, overbooking and pricing for perishable assets called perishable-asset revenue management by the authors. They identified fourteen different aspects of various revenue management models and systematically reviewed the research pertaining to each of these aspects. McGill and Van Ryzin (1999) provided a comprehensive survey of the history of research

* Corresponding author.
E-mail address: kyparis@fiu.edu (G.J. Kyparisis).

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on yield management including forecasting, overbooking, seat inventory control, and pricing. They also provided a glossary of related terms. Bitran and Caldentey (2003) reviewed dynamic pricing models and their applications to revenue management.

Belobaba (1987) reviewed research on the subtopic of airline yield management called seat inventory control and discussed the actual methods utilized in practice. Brumelle et al. (1990) studied the problem of allocating airline seats between two nested-fare classes when the demands are stochastically dependent and generalized the simple seat allotment formula of Littlewood (1972). Netessine and Shumsky (2005) considered the airline yield management problem of optimal allocation of seat inventory among fare classes. They studied this problem under both horizontal competition (when two airlines compete for passengers on the same flight leg) and vertical competition (when different airlines fly different legs of multileg itineraries). Cizaire and Belobaba (2013) analyzed the joint optimization problem of airline pricing and fare class seat allocation generalizing previous research where these two optimization problems were considered separately.

The TCARM problem is similar to a multi-product price-setting newsvendor problem with capacity constraints. In a single-product setting, Van Mieghem and Dada (1999) showed that the optimal capacity is always equal to the order quantity. In contrast, the available capacity is fixed in the TCARM problem.

A comprehensive survey of capacity management models including newsvendor models can be found in Van Mieghem (2003). In the majority of these models, unlike our model, the available capacity is optimized. A different approach was proposed by Murray et al. (2012) with all prices and quantities assumed integer-valued so that the problem reduces to an integer programming problem.

The single-product price-setting newsvendor problem (without capacity constraints) has been extensively studied since the early papers by Whitin (1955), Mills (1959) and Karlin and Carr (1962). An excellent survey of this research (without capacity constraints) was provided by Petruzzi and Dada (1999), followed more recently by Kocabykoglu and Popescu (2011) who studied more general demand models. Zhao et al. (2017) developed a joint pricing and capacity allocation duopoly game theory model with linear additive price-demand functions and bivariate normally distributed joint demand.

The fundamental difference between the TCARM problem and the multiple economy fare problem analyzed in the literature concerns the timing of the demand streams which are assumed sequential in the single-cabin multiple economy fare problem with the discount buyers preceding the last minute full economy fare buyers. On the other hand, business and economy demand streams in the TCARM problem can be assumed concurrent.

We provide a complete characterization of the TCARM problem assuming general multiplicative and isoelastic multiplicative price-demand functions for both cabins. Our findings provide a guide for the optimal cabin partition and the optimal pricing policies for both cabins.

The rest of the paper is organized as follows. In Section 2, we present a general analysis of the TCARM problem. The TCARM problem is analyzed in Section 3 with a multiplicative price-demand function and in Section 4 with a linear additive price-demand function. Some computational experience is reported in Section 5 and the conclusions of this research along with some suggestions for future research are summarized in Section 6.

2. Analysis of the TCARM problem

We consider the TCARM problem with a fixed number of seats K and two cabins (economy and business) with variable prices p_E, p_B respectively in a stochastic demand environment. Our goal is to allocate the total number of seats K so that Q and $K-Q$ seats allocated to economy and business respectively with the objective to maximize the total revenue.

We assume that the overall stochastic demands for economy and business are given by the general stochastic price-demand functions $D_E(p_E) = d_E(p_E, R_E)$ and $D_B(p_B) = d_B(p_B, R_B)$ respectively, where d_E, d_B are deterministic demand functions and R_E, R_B are random variables (random shocks).

The random variable R_i, has cdf F_i, $\overline{F_i}(x) = 1 - F_i(x)$, and pdf f_i with support on $[0, \infty)$ so that $f_i(x) = 0$ for $x < 0$ and $f_i(x) > 0$ for $x \geq 0$, $i = E$, B. We assume that f_i is twice differentiable for $x > 0$ and that the mean $\mu_i = \int_0^\infty x f_i(x)dx$ is finite, $i = E,B$. For any pdf f and cdf F, the failure rate is defined as $h(x) = \frac{f(x)}{\overline{F}(x)}$ and the generalized failure rate as $g(x) = xh(x)$. F is IFR (increasing failure rate) if $h'(x) \geq 0$ (Barlow and Proschan, 1975) and F is IGFR (increasing generalized failure rate) if $g'(x) \geq 0$ (Lariviere and Porteus, 2001). The partial expected value of x with upper limit z is defined as $G(z) = \int_0^z xf(x)dx$.

Let $d(p)$ be a deterministic price-demand function such that $d^{'}(p) < 0$. The price-elasticity index $\eta(p)$ of demand $d(p)$ is defined as $\eta(p) = -\frac{pd^{'}(p)}{d(p)}$. Song et al. (2008) as well as Kocabykoglu and Popescu (2011) discuss the elasticity properties of various demand functions.

The revenue management optimization problem is

$$\max_{p_E, p_B, Q \in [0,K]} \Pi(p_E, p_B, Q) = p_E E[\min(Q, d_E(p_E, x))] + p_B E[\min(K-Q, d_B(p_B, y))], \tag{1}$$

where $E[min(Q, d_E(p_E, x)]$ and $E[\min(K-Q, d_B(p_B, y))]$ are the expected sales of economy and business seats respectively (with the expected values computed using cdfs F_E and F_B respectively).

The additive price-demand model is defined as $d(p,R) = d(p) + R$ and the multiplicative price-demand model is defined as $d(p,R) = d(p)R$ (in order to simplify notation, we utilize the same symbol $d()$ both in the $d(p,R)$ and $d(p)$ expressions). Some authors also utilized a combined additive-multiplicative demand model $d(p,R) = d_1(p)R + d_2(p)$ (Young, 1978) which however becomes intractable with two products.

Petruzzi and Dada (1999) showed that the demand variance is independent of price in the additive case and a decreasing function of price in the multiplicative case. Also, the demand coefficient of variation is an increasing function of price in the additive case but it is independent of price in the multiplicative case.

Taylor (2002) also discussed the differences between additive and multiplicative models in the context of single-product price-setting newsvendor problems, with effort replacing the demand function. He stated that the additive model is more appropriate when the effect of effort on demand is deterministic while the multiplicative model is more appropriate when the effect of effort on demand is stochastic.

An equally important issue is the selection of an appropriate random demand distribution for the TCARM problem. Brumelle et al. (1990) used discrete approximations of bivariate normal distributions to model discount fare/full fare joint probability distributions. Cizaire and Belobaba (2013) considered a two-period pricing and allocation model with linear additive price-demand functions and independent uniformly distributed demands in each period. They stated that even though the normal distribution is typically assumed in the airline revenue management models, there are several reasons why the choice of a uniform distribution is also appropriate for these problems.

The above review motivates the use of either an additive or a multiplicative price-demand model and either a uniform or a normal random demand distribution. Krishnan (2010) provided a thorough analysis of these models for a structurally similar newsvendor problem and observed that the actual demand realization at the optimal price may be negative with a linear additive demand. As a result, he proposed replacing the $d(p) + R = a - bp + R$ demand function with the nonnegative demand function $[a - bp + R]^+ = \max\{a - bp + R, 0\}$ which, according to Krishnan (2010) makes the problem less tractable. Kyparisis and Koulamas (2018) further investigated this issue and showed that the single-period, single-product newsvendor problem with the $[a - bp + R]^+$ demand function is solvable under very restrictive assumptions.

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