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Flying high or falling short? markup and product differentiation in the U.S. airline industry (2002–2022)

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Abstract
The U.S. airline industry experienced dramatic financial performance swings over the past two decades, moving from $31 billion in operating losses (2002–2009) to $163 billion in operating profits (2010–2019), followed by steep losses and a timid recovery during the pandemic (2020–2022). Building on the work of C.A.K. Lovell, this paper introduces a novel framework for decomposing annual markup changes over this period. A key contribution is the inclusion of product differentiation as an economic driver—an often-overlooked factor in traditional financial performance analyses. Using this methodology, we analyze profitability changes across 20 U.S. airlines from 2002 to 2022, offering new insights into the drivers of both industry-wide and firm-level performance dynamics.

Keywords Product differentiation · Output attributes · Profitability decomposition · Price frontier · Financial performance · Revenue function

1 Introduction

The U.S. domestic airline industry swung from $31 billion in losses over the eight-year period from 2002 to 2009, to $163 billion in profits in the subsequent nine-year period from 2010 to 2019. This was followed by the pandemic lockdown in 2020 and the gradual recovery of the sector in the next few years. Using the ratio of revenue to cost as a measure of financial performance, the industry rose from a mean of 1.00 in the first period to 1.13 in the second period. Figure 6 highlights this growth, with a peak of 1.25 in 2015, before dropping some in the pre-pandemic period. A handful of studies have examined this shift in financial performance and put forward some possibilities: Hazel (2018) points to an increase in capacity discipline, Barrows (2018) to recent mergers and airfare increases, and Mccartney (2018) attributes the increase to baggage and other fees. Maung et al. (2022) study the relationship between both growth and profits and find that choice of airline business model affects the relationship. Outside of the U.S. industry fortunes have improved as well, but not to the same degree, introducing a further motivation to understand the drivers of change in the U.S. market. To study this in depth we decompose the ratio of revenue to cost change over the twenty-one-year period and explore the economic drivers, with a focus on product differentiation. We use the revenue-to-cost ratio mainly for two reasons: the first is that it allows for easier comparison between firms and periods of varying size. Second, like profit, it is a measure of financial performance that is understood by both economists and businesspeople because it is interpreted as the firm's markup or margin, as shown in Sect. 2.

The airline industry has previously been studied using different measures of financial performance (Färe et al. 2007; Scotti and Volta 2017; Huang et al. 2021; Maung et al. 2022). However, the effects of product differentiation are not accounted for in these studies, nor in other industries in the wider financial performance change literature. Therefore, a contribution of this paper is to extend the methodological proposals of Grifell-Tatjé and Lovell (2015, 2016, 2018, 2021) by introducing product differentiation as an economic driver in the cost side, revenue side, and profitability defined as the ratio of the two, and thus also as a driver in the financial performance literature. Although the paper analyzes the financial performance behavior of the U.S. airline industry, the proposed methodology can be applied to for-profit or nonprofit firms in any economic sector.

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Product differentiation is typically analyzed for its impact on price and revenue but can also influence cost. This study begins by decomposing cost change into its key drivers: product differentiation and other factors. While the latter has been extensively studied, product differentiation remains relatively unexplored. To address this, we adopt the Allen-type index number introduced by Howell and Grifell-Tatjé (2023) to isolate the effect of product differentiation on cost change. Recognizing that product differentiation also affects revenue, we employ the non-standard revenue function proposed by Berger et al. (1996) to decompose revenue change. Combining this revenue function with a cost function represents the second major contribution of this study.

Cost efficiency, defined as the ratio of observed to minimum cost, typically assumes homogeneous output across firms. However, this assumption often fails, particularly in industries like airlines, where outputs vary in on-time performance, seating density, and service levels. Producing outputs with higher characteristics often requires more inputs and higher costs, meaning efficiency measures that ignore characteristic intensity will be biased. To address this, we measure cost efficiency using a cost function that accounts for product differentiation. While current efficiency literature acknowledges operating environment heterogeneity, it rarely considers product differentiation. In the next section, we distinguish between characteristics that define the operating environment and those that define the product.

Moving to change over time we find a second flawed assumption of standard analysis; that product characteristics are homogeneous between periods. Cost improvements are accredited to drivers such as input price reduction or productivity, not changes in the characteristics of the product. However, in the airline industry, as with many other industries, product characteristics change over time. This raises our second research question, what have been the drivers of cost change over the observation period? How does the effect of change in product differentiation compare to other well-known effects such as productivity? Our third research question asks the same questions as the second but on the side of revenue. With these results we move naturally to profitability change and our fourth question. Combining cost and revenue change, what have been the drivers of profitability change and how important is product differentiation relative to other effects?

We make three contributions in this paper. First, the inclusion of product differentiation to the financial performance measures of cost efficiency, cost change and revenue change. Second, combining a cost function and revenue function allows us to explain profitability change, the ratio of the two, in a novel way. Finally, while U.S. airline financial performance has been the subject of prior research, none have focused on a such a broad period of analysis with wide diversity in profitability. To fully understand the change drivers, we analyze twenty individual carriers in the domestic U.S. airline industry between 2002 and 2022, presenting aggregate results for the entire period of analysis and the three periods, 2002–2009, 2010–2019, and the pandemic and post-pandemic period, 2020–2022.

In the next section we provide a brief review of the literature that forms the structure of the following sections. Our methodology is covered in Sect. 3, the data and empirical application in Sect. 4, results are presented in Sect. 5 and conclusions in Sect. 6.

2 Background

2.1 Output attributes

Currently the efficiency literature accounts for differences in the operating environment. For example, Coelli et al. (1999) research the question of whether to include environment characteristic as factors that shape the technology, or as factors that influence the degree of technical efficiency. They test these alternatives using Stochastic Frontier Analysis and three characteristics, average stage length, aircraft size and load factor. They find that the results provide similar rankings of airlines, but different degrees of technical efficiency. In another airline example, Galán et al. (2014) include characteristics as a form of unobserved firm heterogeneity and find that including the factors of average stage length, points served, and load factor improves predictive performance.

The characteristics that have been included in the literature are operating or environmental characteristics, not differentiating characteristics. The average stage length of a flight can effect firm cost, but from a consumer point of view it does not differentiate products between firms. In this paper we focus on factors that allow firms to differentiate their product from others in the market. As an example, all carriers flying between two city-pairs travel the same distance, but one may have more frequent flights, or better on time performance. To prevent confusion, we follow Ray and Mukherjee (1996) who define these characteristics as "output attributes". With output attributes we focus on differentiation between firms, rather than within the firm, as the attribute is provided equally to all passengers. Differentiation between customers in a firm is an interesting question, however the data does not allow us to measure those cost differences. We contribute to the previous literature by our inclusion of output attribute as differentiating characteristics.

2.2 Performance in the U.S. airline industry

Several studies have explored the potential correlation between service levels and financial performance. Using a non-parametric analysis, Merkert and Pearson (2015) develop an efficiency measure that incorporates perceived service levels, output and operating margin. Their first stage test finds no correlation between service level and operating margin, but a second stage finds that crew size has some effect. Similarly, Kalemba and Campa-Planas (2018) examine the relationship between quality and financial performance by combining four distinct quality measures. Their findings reveal a positive relationship between quality and return on investment, though no significant relationship is found between quality and revenue.

Focusing on changes in profits as a percentage of variable costs, Scotti and Volta (2017) examine the global airline industry during the 1983 to 2010 period. Utilizing a Bayesian cost function estimation and a total factor productivity approach, they conclude that technical advancements increased efficiency; however, these gains largely benefited consumers rather than translating into improved financial performance for the industry. The persistent lack of financial performance in the airline sector has been analyzed by Borenstein (2011), who attributes it to exogenous demand and cost shocks, and by Wojahn (2012), who identifies overinvestment and excess capacity as key factors.

In a more recent exploration of the tension between growth and financial performance, Maung et al. (2022) demonstrate that the airline business model significantly impacts financial outcomes. Using a dynamic system generalized method of moments, they find that low-cost carriers successfully achieve both growth and profit improvements, whereas full-service carriers face inherent trade-offs between these objectives.

The International Air Transport Association (IATA) commissioned a study covering the 2004 to 2011 period, which revealed that while the aviation industry generates substantial value for customers, it struggles to achieve adequate profit. The report attributes this challenge to excess profits in other parts of the value chain and the fragmented nature of the industry. A subsequent IATA (2018) report highlights improved financial performance in North America during the pre-pandemic period of 2010–2019, driven by industry consolidation, ancillary revenue streams, and low fuel prices—findings that align with the conclusions of this paper.

2.3 Profitability

This paper follows in that tradition by examining the U.S. airline industry according to the methodological context defined by C.A.K Lovell. He has made methodological contributions in the accounting and business valuation tradition to the analysis of firm financial performance by defining exact relationships between the measure (revenue, cost, profit, markup, dividend and return on assets) and its explanatory drivers with the assistance of economic theory. Particularly relevant to this research is his contributions to the study of the revenue-to-cost ratio (Brea, Grifell-Tatjé and Lovell 2011; Grifell-Tatjé and Lovell 2015 Ch 2,3; 2016, 2018, 2021), which is called "profitability" based on the work of H.S. Davis in his studies of the U.S. industry in the 1950s. For this reason, in this paper, the term "profitability" is restricted to this specific measure of firm financial performance.

Grifell-Tatjé and Lovell (2015 Ch 2, 3) provide a broad and deep discussion of profitability and profitability change and establish their relationship with very well-known theoretical index numbers such as Könus (1939) and Malmquist (1953). To see the importance of the revenue-to-cost ratio, we can express the price as $p = (1+\delta)uc$, where p is the product price, uc defines the unit cost, and δ is the markup or business margin associated with the product. Profitability is defined as $\Pi = py/w^T x$, where w and x describe vectors of input prices and quantities respectively and "T" is the transpose of the vector, it is easy to show that $\Pi = (1+\delta)$. In the business side, the product margin is usually defined as $(py - w^T x)/w^T x$, which is equal to δ. Therefore, both measures of financial performance provide the same information.

At the corporate level, the organization's margin is given by $(R-C)/C$, where R and C are revenue and cost, respectively. We have: $(R-C)/C = \Pi - 1$ where $\Pi = R/C$ in this context, then to calculate the organization's margin or organization's profitability are equivalent, but profitability Π has the advantage that it is easier to decompose, i.e. to explain. It is also interesting to note that the popular measure of firm financial performance, return on assets (ROA), can be related to profitability. Its definition is $ROA = \pi/A$, where π is profit and A is assets. It can be rewritten as $ROA = \left[1 - \Pi^{-1}\right](R/A)$, where the value of ROA depends on the level of profitability (Π) and the relationship between the firm's revenue and its assets and nothing else. It is interesting to note from the review of the previous Sect. 2.2 that none of the articles mentioned have studied the markup or margin of the U.S. airline industry.

3 Methodology

In this section, we develop the cost efficiency measure and the decompositions of cost, revenue and change in the ratio of cost to revenue – change in profitability - all with a focus on product differentiation.

3.1 A cost approach with output attributes

Beginning with standard notation, we define the vector of output quantities as $y \in \mathbb{R}_{+}^{M}$, output prices as the vector $p \in \mathbb{R}_{++}^{M}$, input quantities as $x \in \mathbb{R}_{+}^{N}$, input prices as $w \in \mathbb{R}_{++}^{N}$, and output attributes as $q \in \mathbb{R}_{+}^{J}$. Ray and Mukherjee (1996) note that in many industries the scalar output produced may have qualitative output attributes, and that the maximum output that can be produced may depend on these attributes. With this in mind, we define production possibility set T as the set of output quantities with associated attributes that can be produced for a given input set as $T = \{(x, y, q) : x\ can\ produce\ y\ with\ attributes\ q\}$. Given technology set T we define the set of inputs required to produce a given output vector quantity with a given vector level of attributes as $L(y, q) = \{x : (x, y, q) \in T\}$.

Adding input prices w, we move from input quantities to a cost function and define the least expensive set of inputs required to produce a given output vector quantity and vector level of attributes. Letting total cost be C = $w^T x$, the minimum cost to produce the vector of output quantities y with input prices w and output attributes q can be found as,

$$c(w, y, q) = min_x \{w^T x : x \in L(y, q)\} . \tag{1}$$

The total cost C = $w^T x$ is bounded below by the cost frontier defined by (1), and it is non-decreasing in y and q, and non-decreasing concave, and homogeneous of degree +1 in w. From (1) we see that minimum cost can increase from an increase in output quantities y or in attributes q. We also see that $w^T x \geq c(w, y, q)$, observed cost will be equal to or greater than the minimum cost. It is worth noting that the increases in the cost function are not only associated with attributes that represent higher product quality. In the applied part of the paper, flight frequency is defined as an attribute. An airline offering two smaller flights per day on a route will require more inputs than the same airline offering one larger flight. Given two options of departure time versus one choice, the traveler is more likely to depart at his preferred time and generate utility. In this example, the increase in the cost function is unrelated to the quality of the output. Similar examples are easy to find in cases where the firm is integrating aspects related to environmental, social, and governance factors, such as carbon emissions, labor practices, human rights, and charitable activities. In fact, output attributes q could be used to capture any form of differentiation just discussed, as well as brand value or network effects, because they can all be converted into a measurable cardinal form.

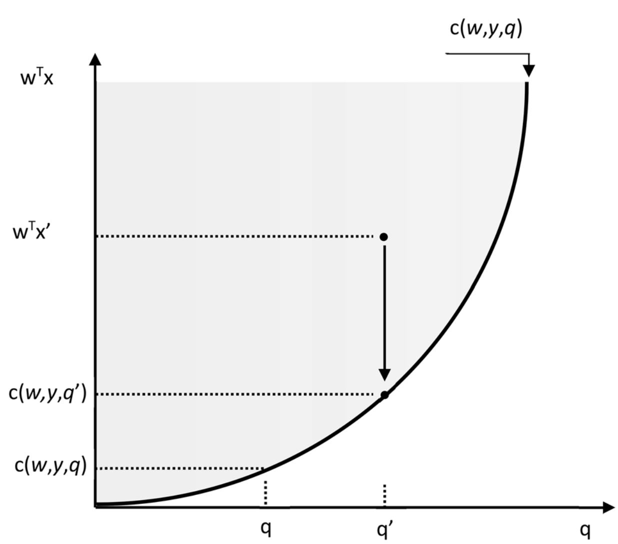


Fig. 1 Cost function with output attributes

With expression (1) we explore our first research question and generate a measure of cost efficiency that accounts for the level of attributes. Expression $c(w, y, q)$ in (1) defines a cost frontier that is non-decreasing in y and q, concave, and homogeneous to the first degree in w. A measure of cost efficiency would be a function of,

$$CE_c(w, y, q, x) = w^T x / c(w, y, q) \geq 1. \tag{2}$$

In expression (2), higher levels of inefficiency are associated with higher values of $CE_c(w, y, q, x)$. Figure 1 depicts a cost function and an observed cost $w^T x'$ associated with the level of attributes q', given w and y. Any observations in the shaded area above the curve have a cost efficiency measure greater than one, as observed cost is greater than minimum cost. In Fig. 1, inefficiency can be visually measured as the vertical distance between observed $w^T x'$ and the function $c(w, y, q')$.

In Fig. 1 we see that at as attributes q increases, minimum cost $c(w, y, q)$ increases, so if $q < q'$ then $c(w, y, q) < c(w, y, q')$. In the introduction, we noted that if differences in attributes between firms were not accounted for, cost efficiency for firms providing a higher level of attributes would be biased upward. For example, if a firm provides attributes q' where $q < q'$, and the assumed level of attributes is q, we would find that $w^T x' / c(w, y, q) > w^T x' / c(w, y, q')$. We see this situation depicted in Fig. 1 where minimum cost $c(w, y, q)$ is less than $c(w, y, q')$, but observed cost $w^T x'$ is driven by the attributes q' not the assumed q.

From (1) we see that product differentiation is a determinant of costs and hence a determinant of cost efficiency as expressed in (2). Moving from static cost efficiency, to the dynamic measure of cost change, the effect of product differentiation then becomes a determinant of changes in cost. Howell and Grifell-Tatjé (2022,

2023) introduce an index of product differentiation as $Q\left(w_h, y_h, q_h^1, q^0\right) = c\left(w_h, y_h, q_h^1\right)/c\left(w_h, y_h, q^0\right)$ where q^0 is the minimum level of attributes in the market and q^1 the observed level of attributes of firm h. This static index of differentiation can be moved to a dynamic context to explain cost changes due to a change in the level of attributes. In the decomposition of the cost change proposed below, q^0 is replaced by q^t and q^1 is replaced by q^{t+1}.

To maintain our focus on attributes, we first decompose cost change by the product differentiation effect, and then into the remaining effects. For this purpose, we adapt to this new context of product differentiation index a method described in Grifell-Tatjé and Lovell (2015: 282) for the situation of a Konüs (1939) index. We separate cost change into two components, a change in attributes and its implicit product differentiation index as,

$$\frac{w^{t+1T}x^{t+1}}{w^{tT}x^t} = \frac{c^{t+1}(w^{t+1},\ y^{t+1},\ q^{t+1})}{c^{t+1}(w^{t+1},\ y^{t+1},\ q^t)} \times \frac{w^{t+1T}x^{t+1}/c^{t+1}(w^{t+1},\ y^{t+1},\ q^{t+1})}{w^{tT}x^t/c^{t+1}(w^{t+1},\ y^{t+1},\ q^t)}. \tag{3}$$

In (3) the first expression on the right defines a product differentiation index in a dynamic context, which measures the change in minimum costs due to a change in attributes holding technology, output, and input price equal to the final period $t+1$. If all or some of the components of the final attribute vector are higher (lower) than the initial $q^{t+1} \geq (\leq)\ q^t$, then the product differentiation index also takes a value higher (lower) than 1. If the attribute levels do not change: $q^t = q^{t+1}$, the product differentiation index is equal to 1. The second expression is an implicit product differentiation index of all other cost change drivers that can be decomposed as,

$$\begin{aligned}\frac{w^{t+1T}x^{t+1}}{w^{tT}x^t} = &\frac{c^{t+1}(w^{t+1}, y^{t+1}, q^{t+1})}{c^{t+1}(w^{t+1}, y^{t+1}, q^t)}\\ &\times \frac{w^{t+1T}x^{t+1}/c^{t+1}(w^{t+1}, y^{t+1}, q^{t+1})}{w^{tT}x^t/c^t(w^t, y^t, q^t)} \times \frac{c^{t+1}(w^t, y^t, q^t)}{c^t(w^t, y^t, q^t)}\\ &\times \frac{c^{t+1}(w^t, y^{t+1}, q^t)}{c^{t+1}(w^t, y^t, q^t)}\\ &\times \frac{c^{t+1}(w^{t+1}, y^{t+1}, q^t)}{c^{t+1}(w^t, y^{t+1}, q^t)}.\end{aligned} \tag{4}$$

At this point we discuss the interpretation of the expressions in (4) and provide a simplified notation that will be useful in the rest of the paper.

The first expression on the right in (4) is the measure of attribute driven cost change defined in (3), which we note as $Q_c^{t+1}\left(w^{t+1}, y^{t+1}, q^{t+1}, q^t\right)$. The second expression, cost efficiency change, measures the decrease (increase) in cost from a firm becoming more (less) efficient. This is measured as the change in the ratio of observed cost to minimum cost, in other words, how much closer (further) the firm is to the cost frontier of the period. Following the notation introduced in expression (2) we note this as $\Delta CE_c\left(w^{t+1},\ w^t, y^{t+1}, y^t, q^{t+1}, q^t, x^{t+1}, x^t\right) = \frac{w^{t+1T}x^{t+1}/c^{t+1}(w^{t+1},\ y^{t+1},\ q^{t+1})}{w^{tT}x^t/c^t(w^t,\ y^t,\ q^t)}$. The third expression, in the second row, measures technical change, or shifts in the cost frontier. It can be understood as the introduction of new techniques or technology that allow production of the same quantity of output and attributes with less inputs. We note technical change as $\Delta T_c\left(w^t, y^t, q^t\right) = \frac{c^{t+1}\left(w^t,\ y^t,\ q^t\right)}{c^t\left(w^t,\ y^t,\ q^t\right)}$.

The fourth expression in (4) is defined as the activity effect and is noted as $A_c^{t+1}\left(w^t, y^{t+1}, y^t, q^t\right) = \frac{c^{t+1}\left(w^t,\ y^{t+1},\ q^t\right)}{c^{t+1}\left(w^t,\ y^t,\ q^t\right)}$. Grifell-Tatjé and Lovell (1999) introduce an activity effect in the context of profit change decomposition, which is further developed and shifted to the cost side in Grifell-Tatjé and Lovell (2015; Ch 6,7). This activity effect is adapted to our context of product differentiation and captures cost increase (decrease) due to higher (lower) provision of undifferentiated products. It measures the cost variation associated with the movement in the quantities of outputs from y^t to y^{t+1} as the increase (decrease) in cost associated with the inputs needed to produce these output quantities. Note that in a general setting of multiple outputs, some output quantities may increase, and others may decrease (or do not increase with the same intensity), resulting in a change in the product mix. This change is captured by the Activity Effect[1]. Assuming constant returns to scale and identical output mix, a doubling of output would mean $A_c^{t+1}\left(w^t, y^{t+1}, y^t, q^t\right) = 2$, signaling that the cost in period t+1 is double that of period t. Therefore, this measure also captures any returns to scale effects and the firm's ability to adjust its output mix based on the level of activity. In this context, where the activity effect is analyzed in isolation, productivity change is given by the product of technical efficiency change and technical change $\Delta CE_c \times \Delta T_c$ in the second row of (4). The justification of this approach is the strong expansion in the industry of aviation, a justification similar to Brea-Solís et al. (2015), who isolate the activity effect for the study of the intensive Walmart expansion policy since its foundation. The final expression in (4) is a Konüs input price index that measures cost change due to changes in input prices maintaining output quantities and attributes, we note it as $W_c^{t+1}\left(w^{t+1}, w^t, y^{t+1}, q^t\right) = \frac{c^{t+1}\left(w^{t+1},\ y^{t+1},\ q^t\right)}{c^{t+1}\left(w^t,\ y^{t+1},\ q^t\right)}$. We use this simplified notation going forward.[2]

[1] Grifell-Tatjé and Lovell (2015: 286).

[2] $\frac{w^{t+1T}x^{t+1}}{w^{tT}x^t} = Q_c^{t+1}(w^{t+1}, y^{t+1}, q^{t+1}, q^t) \times \Delta CE_c(w^{t+1},\ w^t,\ y^{t+1}, y^t, q^{t+1}, q^t, x^{t+1}, x^t) \times \Delta T_c\left(w^t,\ y^t, q^t\right)$

The decomposition in (4) results in a "mixed" period in the factor measuring cost change due to input price change. Mixed in the sense that output y is relative to $t+1$ while attributes q are based on period t[3]. It is also possible to decompose (4) so that the mixed period appears in the measure of activity instead of the measure of input price change. As we do not have clear criterion to prefer one alternative over the other, we take the geometric mean of the two and find activity change as, $A_c^{t+1}\left(w^{t+1}, w^t, y^{t+1}, y^t, q^t\right) = \left[\frac{c^{t+1}\left(w^t, y^{t+1}, q^t\right)}{c^{t+1}\left(w^t, y^t, q^t\right)} \times \frac{c^{t+1}\left(w^{t+1}, y^{t+1}, q^t\right)}{c^{t+1}\left(w^{t+1}, y^t, q^t\right)}\right]^{1/2}$ and input price change as $W_c^{t+1}\left(w^{t+1}, w^t, y^{t+1}, y^t, q^t\right) = \left[\frac{c^{t+1}\left(w^{t+1}, y^{t+1}, q^t\right)}{c^{t+1}\left(w^t, y^{t+1}, q^t\right)} \times \frac{c^{t+1}\left(w^{t+1}, y^t, q^t\right)}{c^{t+1}\left(w^t, y^t, q^t\right)}\right]^{1/2}$. This mixed period only occurs in the factors of input price change and activity change.

Expression (4) is a decomposition from the point of view of technology t+1, the final period. We can also decompose from the point of view of initial period t technology following identical steps as the ones discussed in the case of period t+1 technology. This is possible in our application through the use of sequential technology and generalized returns to scale, as discussed further in the applied section. For example, in a period t technology decomposition attribute change would be $Q_c^t\left(w^t, y^t, q^{t+1}, q^t\right) = \frac{c^t\left(w^t, y^t, q^{t+1}\right)}{c^t\left(w^t, y^t, q^t\right)}$. To weight change equally between the initial and final period we take the geometric mean of the indexes, of the two decompositions based on technology of period t+1 and t. This process is detailed in an addendum. Following this, the final cost decomposition is,

$$
\begin{aligned}
\frac{w^{t+1T}x^{t+1}}{w^{tT}x^t} = \; & Q_c\left(w^{t+1}, w^t, y^{t+1}, y^t, q^{t+1}, q^t\right) \\
& \times \Delta CE_c\left(w^{t+1}, w^t, y^{t+1}, y^t, q^{t+1}, q^t, x^{t+1}, x^t\right) \\
& \times \Delta T_c\left(w^{t+1}, w^t, y^{t+1}, y^t, q^{t+1}, q^t\right) \\
& \times A_c\left(w^{t+1}, w^t, y^{t+1}, y^t, q^{t+1}, q^t\right) \\
& \times W_c\left(w^{t+1}, w^t, y^{t+1}, y^t, q^{t+1}, q^t\right).
\end{aligned} \tag{5}
$$

3.2 A revenue approach with output attributes

Firms engage in product differentiation with the intent of increasing revenue through raising willingness to pay and price. The level of attributes is a lever that firms use to differentiate, therefore we should be able to capture the effect of attributes on revenue and on profitability. In the standard revenue function, firms are thought to maximize revenue by maximizing output quantities y based on given market output price p and fixed inputs x, the function is given as $r(x, p)$. This is analogous to the cost minimization model discussed in the previous section.

However, firms have more control over their level of inputs than over the quantities that they sell. For example, during the period under observation there were three exogenous occurrences at least that significantly changed outputs: September 11th, the 2008 recession and the 2020 pandemia. Since many U.S. routes are monopoly or oligopoly markets airlines have some control over output prices.[4] This is also evidenced by the dynamic pricing systems that play a large role at airlines and are based on the ability to manage prices. In recognition of this we begin with the nonstandard maximum revenue function (NSRF) introduced by Berger et al. (1996) and extend it to include output attributes. Their work specifies this alternative function for the banking industry; however, Cantos and Maudos (2001) applied it to the case of railroads, Cummins et al. (2010) to the insurance industry and Boto-García et al. (2024) to the restaurant industry. We argue that the same conditions cited to justify use of the NSRF in the literature exist in the airline industry.

The NRSF assumes that the firm has some control over their output prices, which Berger et al. (1996) support by pointing to studies showing price dispersion for loan pricing to the same type of borrower. They also cite studies showing that under greater local concentration, banks pay lower rates to depositors and charge higher rates to borrowers. In similar studies on the airline industry Gerardi and Shapiro (2009) and Dai et al. (2014) both document higher levels of price and price dispersion in more concentrated markets, an indication of airlines exercising market power.

The other assumption of the NSRF is the exogenous nature of output. Berger et al. (1996) note that deposit funded outputs can only expand through the growth of the local market or through mergers or acquisitions, offering managers limited ability to maximize revenue by expanding output. Similarly, expansion of output in airline markets is limited to growth in the city pairs served and airport capacity, leaving managers little ability to effect output in the intermediate term.

The NSRF includes input prices w as an argument. In the banking industry, Berger et al. (1996) argue that input prices signal willingness to pay, and that marking up the cost of funds is a bank pricing method. In the airline industry our inclusion is justified by the industry-wide pass-through

$\times A_c^{t+1}\left(w^t, y^{t+1}, y^t, q^t\right) \times W_c^{t+1}\left(w^{t+1}, w^t, y^{t+1}, q^t\right)$ restates (4).

[3] In a study of symmetric decompositions Balk and Zofío (2020) raise the topic of mixed periods.

[4] Howell and Grifell-Tatjé (2022) find that 73% of US non-stop routes are served by only one or two carriers.

nature of fuel prices. Price increases, or fuel surcharges, show up as output price in our model and are common in the industry. A similar argument can be made for airport charges. As the NSRF maximizes price, instead of the level of output, another argument for including input prices would be the textbook description of the relation of price to marginal cost.

With exogenous output quantities and input prices, and some ability to alter prices, the NSRF maximizes revenue as a function of y and w with $r\,(y, w)$. To maximize revenue, a firm transforms output y and input prices w to maximum possible prices p. Extending this, Humphrey and Pulley (1997) add a vector of factors z that influence competitive position and willingness to pay. Combined, these form what they term a bank's *pricing* opportunity set for transforming given y, w and z into maximum output prices. This set contains all feasible combinations of output quantities, input prices, and factors z.

In an article that introduces the possibility of inefficiency to the NSRF, Restrepo-Tobón and Kumbhakar (2017) show that the pricing opportunity set is closed and that a frontier can be defined of the highest feasible price for any given combination of input prices and other factors. With inefficiency, a firm may be operating inside that frontier, charging prices that are less than efficient. Since output levels are given, observed lower than efficient output prices implies revenue inefficiency. The article goes on to find profit efficiency change as a function of revenue efficiency change and cost efficiency change.

Building on this, we replace vector z with output attributes q and formally define a price output frontier as,

$$V = \{(p, w, y, q) : p\ can\ be\ achieved\ with\ w\ and\ q\ at\ output\ quantity\ y\}. \qquad (6)$$

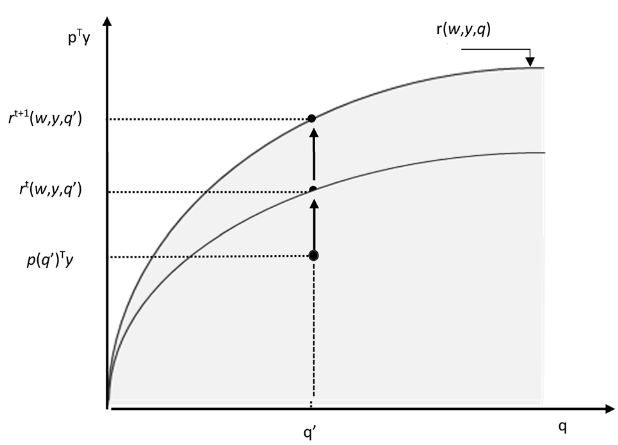


Fig. 2 Revenue function with output attributes

Given V we can define price opportunity set $S(w, y, q) = \{p : (p, w, y, q) \in V\}$ as the set of output prices achievable given w, y and q. Now letting total revenue be R = $p^T y$, the maximum revenue achievable with quantity y, input prices w and attributes q can be found as,

$$r\,(w, y, q) = max_p \left\{ y^T p : p \in S(w, y, q) \right\}. \qquad (7)$$

The total revenue R = $p^T y$ is bounded above by the revenue frontier defined by (7), and it is assumed that this revenue frontier $r\,(w, y, q)$ is non-decreasing in w and q, and non-decreasing, convex and homogeneous of degree +1 in y.

The production technology defined earlier in Sect. 3.1, $T = \{(x, y, q) : x\ can\ produce\ y\ with\ attributes\ q\}$, and the price technology defined in expression (6) are separate and distinct technologies because they define different business realities. The first defines the possibilities in transforming inputs into outputs with attributes, the second represents the possibilities in transforming input prices and a product with attributes into an output price. Based on the first case, a cost function is defined in (1). The second situation allows the definition of a revenue function in (7). Note that both definitions are functions of w, y and q. This approach analyzes whether the firm is able to produce at minimum cost while selling at the highest possible product price. Hence, the T and V technology sets capture different portions of the firm's process,

Figures 2 and 3 are provided to explain the NSRF and how output attributes q affect revenue. Figure 2 shows the relationship between the level of output attributes q on the horizontal and revenue $p^T y$ is on the vertical axis. The revenue frontier envelopes all feasible combinations within the shaded area, but only those on the curve would be considered efficient. Since this function maximizes revenue through price, revenue level $p(q')^T y$ would be an inefficient point because the firm could be charging a higher price. From this we can also see that higher levels of q allow for greater revenue through a higher price. In this figure technical change would appear as a shift upward of the curve from to .

Figure 3 also has revenue $p^T y$ on the vertical axis, but now input prices w are on the horizontal. This depiction represents the pricing opportunity set, with each point shown a feasible combinations of input prices and output prices given the output quantity and the level of attributes. Letting $q'' > q'$, revenue frontier $r(w, y, q')$ envelopes the combinations feasible at attribute level q' in the light gray, and the frontier $r(w, y, q'')$ in dark gray for attribute level q''. Only those observation on the curves are considered efficient. Holding input price and output quantity equal, we see how greater attribute levels allow for higher prices and revenue levels. Like the case of technical change in Fig.2, there is a shift upward of the curve $r(w, y, q')$ and $r(w, y, q'')$

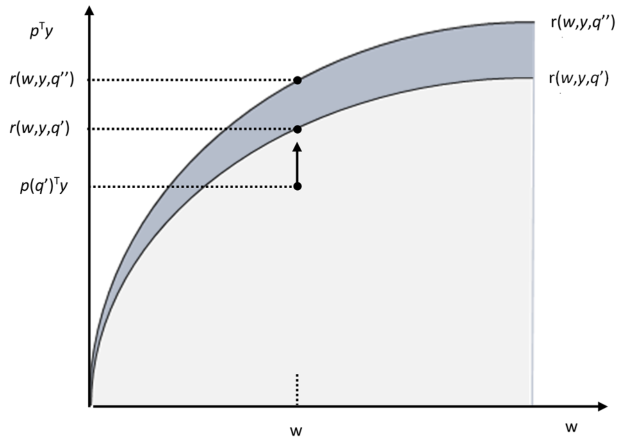


Fig. 3 Revenue function and price frontier

reflecting higher willingness to pay for attributes at level q''.

Following the decomposition method from Sect. 3.1, we break down revenue change between initial period t and final period $t+1$. Focusing on output attributes, we begin with an index of revenue change based on change in output attributes as,

$$\frac{p^{t+1T}y^{t+1}}{p^{tT}y^{t}} = \frac{r^{t+1}(w^{t+1},y^{t+1},q^{t+1})}{r^{t+1}(w^{t+1},y^{t+1},q^{t})} \times \frac{p^{t+1T}y^{t+1}/r^{t+1}(w^{t+1},y^{t+1},q^{t+1})}{p^{tT}y^{t}/r^{t+1}(w^{t+1},y^{t+1},q^{t})}. \tag{8}$$

In expression (8) the first index on the right measures the change in maximum revenue due to a change in attributes holding the technology, output, and prices all equal to the final period. As with the cost decomposition, the second expression is a revenue implicit product differentiation index of all other change drivers and can be decomposed as the cost function in the previous subsection 3.1. Maintaining the same notation as (5), which express the geometric mean of the two technologies t and t+1, with a change of subscript, our full revenue decomposition is,

$$\begin{aligned}\frac{p^{t+1T}y^{t+1}}{p^{tT}y^{t}} = {} & Q_r\left(w^{t+1},w^{t},y^{t+1},y^{t},q^{t+1},q^{t}\right)\\ & \times \Delta CE_r\left(w^{t+1},\, w^{t},y^{t+1},y^{t},q^{t+1},q^{t},x^{t+1},x^{t}\right)\\ & \times \Delta T_r\left(w^{t+1},w^{t},y^{t+1},y^{t},q^{t+1},q^{t}\right)\\ & \times\ A_r\left(w^{t+1},w^{t},\, y^{t+1},y^{t},q^{t+1},q^{t}\right)\\ & \times\ W_r\left(w^{t+1},w^{t},y^{t+1},y^{t},q^{t+1},q^{t}\right).\end{aligned} \tag{9}$$

A full description of generating (9) is shown in an addendum. The first expression on the right of (9) measures change driven by a change in the level of attributes. In terms of the price output frontier, this can be thought of as a higher level of attributes allowing a greater maximum price and revenue, the situation displayed by Fig. 3. The second expression measures change in revenue efficiency, values greater than one indicate that the firm's prices are closer to the optimal prices in period $t+1$ compared to period t. A value equal to one indicates no change in revenue efficiency, while a value less than one indicates that the firm's prices have moved further away from the optimal prices in period $t+1$ compared to period t. The third expression measures frontier shifts from change in factors such as consumer sentiment or market power, altering the maximum revenue and output price achievable for a given w, y and q. In combination, the second and third expressions measure what we consider productivity in the cost function. To differentiate, we refer to these two as "price productivity". The fourth expression is a measure of how operating at a different output quantity (or activity level) changes revenue, that is $y^t \neq y^{t+1}$ and the final a measure of how changes in input prices w change revenue.

3.3 Profitability change and output attributes

We are now ready to combine cost and revenue change into a measure of profitability change. This is not a standard pairing, however, since these functions are based on distinct technologies the combination does not duplicate technology related effects, an aspect stressed by Restrepo-Tobón and Kumbhakar (2017). Defining profitability as $\Pi = R/C$, we find profitability change between periods as $\Pi^{t+1}/\Pi^{t} = (R^{t+1}/C^{t+1})/(R^{t}/C^{t})$ or $\Pi^{t+1}/\Pi^{t} = (R^{t+1}/R^{t})/(C^{t+1}/C^{t})$, which can be restated as,

$$\Pi^{t+1}/\Pi^{t} = \frac{p^{t+1T}y^{t+1}}{p^{tT}y^{t}} / \frac{w^{t+1T}x^{t+1}}{w^{tT}x^{t}}. \tag{10}$$

Replacing the final expression on the right in (10) with expressions (5) and (9), and shortening the notation, we decompose profitability change as,

$$\frac{p^{t+1T}y^{t+1}}{p^{tT}y^{t}} / \frac{w^{t+1T}x^{t+1}}{w^{tT}x^{t}} = \frac{Q_r}{Q_c} \times \left[\left(\Delta RE \times \Delta CE^{-1}\right) \times \left(\Delta T_r \times \Delta T_c{}^{-1}\right)\right] \times \frac{A_r}{A_c} \times \frac{W_r}{W_c}. \tag{11}$$

We interpret the first expression on the right in (11) as the change in profitability driven by a change in output attributes, and define it as $QPI\left(w^{t+1},w^{t},y^{t+1},\, y^{t},q^{t+1},q^{t}\right)$ or *the attribute profitability index*. The numerator captures the increase in maximum revenue and output price achievable with the change in attributes, while the denominator measures the associated change in cost. When $QPI\left(w^{t+1},w^{t},y^{t+1},\, y^{t},q^{t+1},q^{t}\right) > 1$ the change in output attributes contributes positively to profitability,

$QPI\left(w^{t+1}, w^{t}, y^{t+1}, y^{t}, q^{t+1}, q^{t}\right)=1$ would indicate that the increase in cost has been matched by the increase in revenue and when $QPI\left(w^{t+1}, w^{t}, y^{t+1}, y^{t}, q^{t+1}, q^{t}\right)<1$ the variation in cost associated with the decision to change attributes is not compensated by the change in revenue i.e. a higher output price.

The effects for the next four expressions, revenue efficiency, cost efficiency, revenue technology, and cost technology combine to measure the effect of productivity change on profitability. In (11), the expressions associated with the revenue and cost functions are presented separately. This allows us to discuss the technical efficiency change and technical change in the cost and price-revenue functions separately in Sect. 5. The interpretation of these expressions in (11) thus are the same as the interpretation of their counterpart in (5) and (9), although cost changes are presented as the inverse, as an increase in cost reduce profitability.

The next expression in (11) measure the effect on profitability of operating at a different level of activity. It can be understood as the contribution of both output and input mix changes, as well as the contribution of "scale economies" to profitability, which are associated with the denominator of the expression, i.e. A_c, given the homogeneity of degree + 1 in y of the revenue function. The numerator measures revenue change associated with the move from y^t to y^{t+1} and the associated cost change for the same output quantity change in the denominator. When the value of $A_r/A_c>1$ the change in output quantity contributes positively to profitability, when $A_r/A_c=1$ the increase in cost has been matched by the increase in revenue and when $A_r/A_c<1$ the variation in cost associated with output quantity change is not compensated by the revenue change. The final expression measures the effect of a change in input prices on profitability. The denominator indicates how this affects minimum cost, and the numerator how the input price change is translated to output prices. The resulting value can be interpreted in a similar way to the description of activity effects. The introduction of a price output frontier to measure revenue change allows for measures of profitability change not typically captured and is one of the primary contributions of this paper.

4 Data and method

4.1 Data

The primary source of data for this article is Form 41 of the U.S. Department of Transportation (DOT). By law, most passenger and cargo carriers are required to report operational and financial information to the DOT monthly, quarterly, or semi-annually. We have only included domestic U.S. operations to allow for an equal comparison of firms and product as the stage length of international flights are much longer. To reduce variation due to seasonality, the unit of analysis is annual operating profitability change, providing 256 observations of profitability change for sixteen carriers between 2002 and 2022. Descriptive statistics are presented in Table 1.

To highlight the disparity in profitability between the periods we present profitability and profitability change for two periods separately, and then annually for 2020–2022. As can be seen, profitability in the latter period 2010–2019 is 12.0% having been virtually zero during the earlier period 2002–2009 as reflected by the 1.00 average profitability measure. Revenue varies widely, with a maximum revenue of ~$22 billion recorded by Delta in 2022 and a minimum of $367 million by Spirit Airlines in 2002.

To estimate the cost and revenue functions we use a standard model, with capital, labor, fuel and other materials as inputs, and passenger miles and freight transported as outputs. The inputs of labor and fuel are relatively straightforward to calculate. We use the number of full-time equivalents (FTE) as the quantity of labor, with total salaries and benefits divided by labor quantity as the price. Since we analyze operating profitability, both the quantity and salary of general management has been removed. The quantity of fuel is found as total domestic gallons, with total domestic fuel cost divided by gallons as the price. Since fuel is a significant share of total cost, and has been the most volatile price over time, we provide some historic detail on this input. In Fig. 4 we can see that fuel prices were steadily growing over the first period 2002–2009, rising from under $1 a gallon to peak at over $4 a gallon in mid- 2008. Between 2009 and 2019 prices rose and fell but stayed between $1 - $3 per gallon. The Covid Pandemic drove a steep decline in 2020, followed by a sharp increase up to $5 gallon by 2022. Due to these swings, fuel as a share of total operating expense has ranged from a low of 6% to a high of 53%.

Following Färe et al. (2007) we define capital quantity as the number of seats available based on planes in service and their configuration. The price of capital is found as actual firm leasing costs and depreciation, divided by capital quantity. The final input, other materials is found as total operating costs less all other identified inputs. Quantity is calculated by deflating the total by the Bureau of Labor Statistics producer price index of air transport activities and the producer price index defines the associated price.

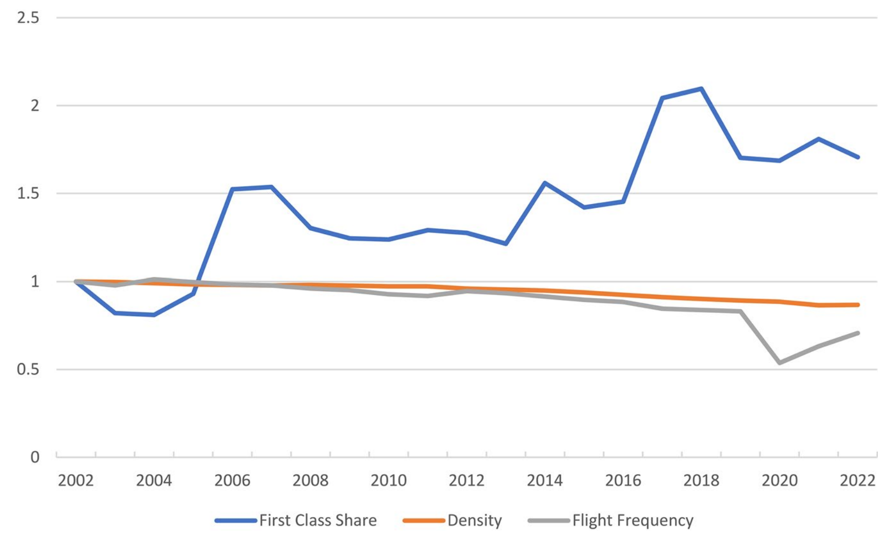
We use two measures of output, revenue passenger miles (RPM) and the ton miles of freight and mail carried. Passenger miles is by far the most important output, generating over 98% of revenue, and a number of carriers do not even carry freight or mail. Recognizing that airline revenue increasingly comes from sources other than the base fare, we find the price per

Table 1 Descriptive Statistics

Variable	Mean	Std. Dev	Min	Pctl(25)	Pctl(75)	Max
2002 - 2009						
Profitability	1.00	0.09	0.79	0.93	1.06	1.21
Profitability Change	1.01	0.07	0.82	0.96	1.05	1.18
2010 - 2019						
Profitability	1.13	0.10	0.92	1.06	1.18	1.44
Profitability Change	1.01	0.06	0.85	0.97	1.05	1.24
2020						
Profitability	0.61	0.09	0.48	0.55	0.69	0.76
Profitability Change	0.54	0.07	0.41	0.49	0.59	0.62
2021						
Profitability	0.90	0.07	0.81	0.85	0.94	1.04
Profitability Change	1.49	0.17	1.22	1.37	1.62	1.69
2022						
Profitability	1.02	0.06	0.90	0.97	1.06	1.09
Profitability Change	1.13	0.08	1.01	1.08	1.18	1.23
2002 - 2022						
Operating Revenue	$5,667,692	$5,524,946	$366,359	$1,086,654	$9,182,385	$21,709,500
Operating Expense	$5,524,337	$5,225,159	$356,124	$968,538	$9,756,412	$19,942,460
Capital Qty	38,553	33,275	2,029	10,801	66,391	112,954
Capital Price	$11.02	$4.30	$3.49	$8.25	$13.38	$35.90
Labor Qty	22,454	20,574	642	4,306	39,555	74,821
Labor Price	$66.27	$15.01	$36.07	$55.65	$75.92	$127.20
Fuel Qty	768,736	649,944	71,173	188,809	1,302,035	2,312,267
Fuel Price	$1.50	$0.52	$0.59	$1.08	$1.94	$2.69
Other Materials Qty	21,501	22,764	495	3,139	33,764	94,683
Other Materials Price	$113	$2	$109	$111	$115	$116
Passenger Miles Qty	38,200	31,963	3,361	9,637	64,898	127,868
Passenger Miles Price	$121.43	$27.21	$70.06	$100.88	$139.86	$181.40
Property Tons Qty	153.43	179.20	0.00	7.16	245.35	662.40
Property Tons Price	$442.51	$320.65	$4.38	$272.14	$578.01	$1,297.28
First Class Share	0.02	0.02	0.00	0.00	0.02	0.12
Density	160.81	27.83	113.35	143.75	168.16	257.38
Flight Frequency	4.93	2.58	0.43	3.67	5.96	14.90

Fig. 4 Kerosene-type jet fuel prices: US gulf coast

Fig. 5 Output attributes indexed to 2002



RPM as all operating revenue not identified as freight or mail, divided by the quantity of RPM. This measure then includes any ancillary charges for services such as baggage fees, cancellation fees, or food sales. In short, all revenue derived from transporting passengers. The price for the second output is found as freight and mail revenue divided by the quantity.

We use three output attributes that differentiate the product provided. The first is first class share, measured as the percentage of tickets sold that are in first or business class. It serves as a measure of overall service level and is sourced from the DB1B, a 10% sample of all tickets sold. The second attribute, frequency of flight, is a measure of convenience and has been noted by Borenstein (1989) and Douglas and Miller (1974) as a product differentiator that increases the value of the brand to consumers. Since flight frequency is only relevant at the point of departure, we measure it as an average of departures per day, per route. The last attribute, density, the number of seats per plane, can be thought of as a physical measure of a service product. Over the period under observation, density increased from an average 151 seats per plane to almost 178 seats. This corresponds with reports that show that seat pitch, the distance between seat rows, has declined from 89 to 78 cm, and that seat width has dropped from 46 to 43 cm over roughly the same period[5]. These all indicate that the amount of space allocated to a passenger has seen a 10% reduction. Density is calculated as the available seat miles divided by aircraft miles.

In the applied portion we orient the variables so that all indicate increases in q. To that end we measure density as the inverse. As can be seen in Fig. 5, which indexes all measures[6] to 2002 values, all except first class share have drifted downwards over the period. In 2020, during the pandemic, frequency dropped as flights were curtailed. All input and output prices are deflated by the consumer price index.

Including the three variables of product differentiation, first class share, seating density and flight frequency as part of a revenue function does introduce the potential for endogeneity issues. While our use of DEA as the method of frontier estimation mitigates the concern of endogeneity, it does not completely remove it. Cordero, Santín and Sicilia (2025) study the effects of endogeneity in DEA and find that a moderate to high level of positive correlation between the quantity of an input and the efficiency term can create an incorrect estimation of the production frontier. This is not the case for negative endogeneity. We test for this potential in the revenue function defined by (7) and find that first class share shows a negative correlation to revenue efficiency and that seating density has no correlation. The attribute of flight frequency does appear to have a low level of positive correlation with efficiency, though this relationship only appears to be in certain clusters of observations. Full details of the three tests we employed, along with a discussion of DEA and endogeneity in relation to our model can be found in the Addendum Part B.

4.2 Empirical method

Our final profitability decomposition in (11) requires estimating minimum cost $c(w, y, q)$ from expression (1) and maximum revenue $r(w, y, q)$ defined in expression (7). The estimation techniques generally used fall into two classes, parametric and non-parametric. In this article we apply the well-known non-parametric data envelopment analysis (DEA) introduced by Charnes et al. (1978). Unlike parametric methods, DEA does not require assumptions on the functional form of the technology. This feature is attractive in modelling the effect of attributes on revenue with the price

[5] Sarkis, Stephen (24 Feb 2020). Airlines' Seat Pitch Gets Shorter and Passengers Reach Their Limits", www.Forbes.com.

[6] Average measures are weighted by passenger miles.

output frontier, a relatively unexplored factor with no well-established form.

Operationalizing DEA requires a selection of returns to scale. The two most commonly used are constant returns to scale (CRS) and variable returns to scale (VRS). Under CRS all changes are proportional, while under VRS the model allows for sections of increasing, constant and then decreasing returns to scale. Under VRS the production frontier envelopes the existing observations more closely, however, this creates a problem in the type of cross period modelling we are doing and can result in infeasible solutions[7]. To counter this, but not enforce the proportionality assumptions of CRS, we assume the generalized returns to scale (GRS) outlined in (Podinovski 2004). Under GRS the technology is allowed to alternate between sections of increasing and decreasing returns to scale. This form fits well with our application to the airline industry where there are roughly three clusters of scale: large national network carriers, medium size national carriers and smaller regional carriers. GRS allows each cluster to have an increasing constant and decreasing return portion within an overarching technology.

In DEA, the best practice frontier is created as an envelope of observed input and output sets. This envelope can be created from contemporaneous observations, meaning that only observations from the current period are used, or use a sequential method, where all current and previous observations are included. In this article we employ the sequential method[8], implying the absence of technical regress, which is reasonable for this industry. It also creates a wider pool of observations, allowing us to include more explanatory variables. To establish a base technology, we include observations beginning from 1998, but only report results for the period 2002 to 2022. To operationalize this in the DEA linear program below we define the 1998 to 2001 period as $t=0$ and 2002 as $t=1$, 2003 as $t=2$, and so on.

To generate the cost and revenue estimations required for (11) we solve the following two DEA linear program problems for each observation of firm h with w, y and q values of the required periods. To implement GRS in DEA we constrain intensity vector λ between a lower bound U and an upper bound L. We set values for the lower and upper bound that generated a frontier that fit the observations as close as possible while generating feasible solutions. The linear program on the left solves for minimum cost given input price vector w, attributes q and output vector y by minimizing inputs x, i.e. expression (1). The program on the right solves for maximum revenue given input price vector w, attributes q and output vector y by maximizing output price p, i.e. expression (7).

$$
\begin{aligned}
& c(w_h, y_h, q_h) = \min_{x,\lambda} w_h^T x && r(w_h, y_h, q_h) = \max_{P,\lambda} y_h^T p \\
& s.t. \sum_{t=0}^{T} \sum_{k=1}^{K} \lambda_k^t x_{km}^t \le x \quad m = 1,\dots,M && s.t. \sum_{t=0}^{T} \sum_{k=1}^{K} \lambda_k^t p_{kn}^t \le p \quad n = 1,\dots,N \\
& \sum_{t=0}^{T} \sum_{k=1}^{K} \lambda_k^t q_{kl}^t \ge q_{hl} \quad l = 1,\dots,J && \sum_{t=0}^{T} \sum_{k=1}^{K} \lambda_k^t w_{km}^t \le w_{hm} \quad m = 1,\dots,M \\
& \sum_{t=0}^{T} \sum_{k=1}^{K} \lambda_k^t y_{kn}^t \ge y_{hl} \quad n = 1,\dots,N && \sum_{t=0}^{T} \sum_{k=1}^{K} \lambda_k^t q_{kl}^t \le q_{hl} \quad l = 1,\dots,J \\
& U \le \sum_{t=0}^{T} \sum_{k=1}^{K} \lambda_k^t \le L, \quad \lambda_k \ge 0. && U \le \sum_{t=0}^{T} \sum_{k=1}^{K} \lambda_k^t \le L, \quad \lambda_k \ge 0.
\end{aligned}
\tag{12}
$$

5 Results

5.1 Cost efficiency

To answer our first research question, we generate the cost efficiency measure defined in (2) that includes product differentiation. The results are presented in Table 2, recall that

Table 2 Mean cost efficiency

Year	$w^T x/c(w, y, q)$	$w^T x/c(w, y)$
2002	1.183	1.244
2003	1.256	1.323
2004	1.303	1.370
2005	1.306	1.359
2006	1.314	1.387
2007	1.317	1.376
2008	1.327	1.385
2009	1.341	1.403
2010	1.280	1.341
2011	1.288	1.336
2012	1.260	1.278
2013	1.247	1.261
2014	1.243	1.261
2015	1.246	1.264
2016	1.256	1.276
2017	1.253	1.282
2018	1.251	1.276
2019	1.248	1.279
2020	2.393	2.509
2021	1.488	1.536
2022	1.338	1.372
Total	1.325	1.370

[7] See (Ray and Mukherjee 1996) for a full discussion of this issue.

[8] See Tulkens and Vanden Eeckaut (1995) for a discussion of this method and Alam and Sickles (2000) for an application to the airline industry.

Table 3 Cumulative growth effect

	2002 - 2022	2002 - 2009	2010 - 2019	2020	2021	2022
Cost Change	**3.12**	**1.32**	**1.83**	**0.77**	**1.17**	**1.26**
Attributes	1.06	1.06	1.00	1.00	1.01	1.00
Productivity	0.80	0.86	0.88	1.92	0.62	0.90
Efficiency	1.22	1.16	1.01	1.92	0.62	0.90
Technical	0.65	0.75	0.88	1.00	1.00	1.00
Activity	2.89	1.26	2.16	0.43	1.78	1.27
Input Price	1.27	1.15	0.97	0.93	1.05	1.11
Revenue Change	**3.24**	**1.45**	**1.94**	**0.41**	**1.73**	**1.42**
Attributes	0.87	0.99	0.91	0.96	0.99	1.02
Productivity	1.33	1.15	1.05	1.08	0.90	1.08
Efficiency	1.05	1.00	0.98	1.05	0.90	1.07
Technical	1.27	1.15	1.06	1.03	1.00	1.00
Activity	3.14	1.38	2.12	0.40	1.91	1.28
Input Price	0.89	0.92	0.95	0.97	1.02	1.01
Profitability Change	**1.04**	**1.09**	**1.06**	**0.53**	**1.48**	**1.13**
Attributes	0.82	0.93	0.91	0.97	0.98	1.02
Productivity	1.67	1.33	1.19	0.56	1.44	1.20
Efficiency - Cost	0.82	0.87	1.00	1.05	0.90	1.07
Efficiency - Rev	1.05	1.00	0.98	0.52	1.61	1.11
Technical - Cost	1.53	1.34	1.14	1.03	1.00	1.00
Technical - Rev	1.27	1.15	1.06	1.00	1.00	1.00
Activity	1.09	1.10	0.98	0.94	1.07	1.01
Input Price	0.70	0.80	0.99	1.05	0.97	0.91

values closer to one indicate higher efficiency level. For comparison purposes we have included the more common measure of cost efficiency as $w^T x/c(w,y)$. A measure that includes the effect of output attributes will always be lower than or equal to a measure that excludes them. To our knowledge, this method of measuring efficiency is new to the literature and is one of our primary contributions. As such, we cannot compare our results to previous studies, however the results for the measure that excludes attributes are similar to those found by Scotti and Volta (2017) in the study of the change in profits as a percent of variable costs and by Assaf (2009) in a study of technical efficiency.

We can see that the gap between the two measures has declined over time, an effect that could be explained by a reduction in product differentiation. As full-service carriers (FSC) have tried to reduce cost and emulate low-cost carriers (LCC), the differences between carriers have diminished. This explanation is supported by Bitzan and Peoples (2016) who find evidence of cost convergence between LCC and FSC.

5.2 Cost change

Following a format from Grifell-Tatjé and Lovell (2008), we present cumulative industry results for the period 2002 to 2022, cumulative results by the two subperiods, and annual results for the Pandemic and post-Pandemic period in Table 3. The values are the geometric average of the period and are standardized to the 2001–2002 change providing an industry cumulative growth effect. For example, the value of 3.12 in the first row of "Cost Change" indicates that cost more than tripled, growing by 212% over the entire period 2002–2022. Each subperiods is measured separately to highlight differences and the second period 2010–2019 is standardized to the 2009–2010 change. Overall cost grew by 32% in the first period 2002–2009, and by 83% in the second period. Results for carriers that were active over the entire period are shown in Table 4 for the 2002 to 2019 cumulative period. We exclude the pandemic period from Table 4 because the extreme changes of that period can skew results at the individual carrier level.

Our driver of primary interest, attribute change, adds 6% to industry cost in the first period, but is flat in the period 2010–2019. In the details by carrier in Table 4, we can observe the impact of business strategy on attribute change. For example, the 11% cost increase from attribute change at Alaska Airlines was largely driven by a rise in first class shares when the carrier implemented its "Alaska 2010" plan to maintain differentiation.[9] This example highlights the discontinuous feature of attribute change driven by discrete strategy changes. Additionally, once the change occurs the firm tends to stay at the new level.

Productivity change has reduced industry cost overall by 20%, with a 14% reduction in the first period and 12%

[9] https://aviationstrategy.aero/newsletter/Dec-003/2/Alaska%3A_the_smallest_Major_the_biggest_turnaround.

Table 4 Cumulative growth effect (2002–2019)

	American	Alaska	JetBlue	Delta	Frontier	Hawaiian	Spirit	United	Southwest
Cost Change	**1.57**	**3.09**	**14.40**	**1.86**	**3.44**	**2.17**	**5.69**	**1.29**	**2.72**
Attributes	1.06	1.11	1.04	0.97	1.00	1.01	1.01	0.99	1.00
Productivity	0.73	0.44	0.77	0.95	0.47	0.64	0.47	0.81	0.65
Efficiency	1.09	0.96	1.46	1.32	0.70	1.07	0.86	1.13	1.10
Technical	0.68	0.46	0.53	0.72	0.68	0.60	0.54	0.72	0.59
Activity	1.68	4.99	12.34	1.60	6.33	2.65	8.73	1.45	2.99
Input Price	1.20	1.26	1.45	1.27	1.14	1.26	1.38	1.10	1.40
Revenue Change	**2.08**	**3.58**	**13.69**	**2.26**	**3.66**	**2.55**	**6.27**	**1.75**	**2.72**
Attributes	0.91	0.84	1.06	0.73	0.60	1.10	0.84	0.92	0.88
Productivity	1.47	0.94	1.01	1.94	0.90	0.85	0.84	1.50	1.44
Efficiency	1.26	0.90	0.88	1.25	0.79	0.80	0.74	1.34	1.04
Technical	1.16	1.04	1.15	1.55	1.14	1.07	1.14	1.12	1.39
Activity	1.84	4.29	12.59	1.79	8.10	2.57	9.41	1.59	2.81
Input Price	0.85	1.05	1.01	0.90	0.83	1.06	0.95	0.80	0.76
Profitability Change	**1.32**	**1.16**	**0.95**	**1.21**	**1.07**	**1.18**	**1.10**	**1.36**	**1.00**
Attributes	0.86	0.76	1.02	0.75	0.60	1.08	0.83	0.92	0.88
Productivity	2.00	2.11	1.31	2.05	1.91	1.33	1.79	1.84	2.23
Efficiency - Cost	1.26	0.90	0.88	1.25	0.79	0.80	0.74	1.34	1.04
Efficiency - Rev	0.92	1.04	0.69	0.76	1.43	0.94	1.16	0.89	0.91
Technical - Cost	1.16	1.04	1.15	1.55	1.14	1.07	1.14	1.12	1.39
Technical - Rev	1.48	2.16	1.89	1.39	1.48	1.67	1.84	1.39	1.70
Activity	1.10	0.86	1.02	1.12	1.28	0.97	1.08	1.10	0.94
Input Price	0.70	0.83	0.70	0.71	0.73	0.84	0.69	0.73	0.54

in the second. In the first period technology improvements reduced costs by 25%, meaning that shifts in the frontier reflected a lower minimum cost, while over the same period efficiency change raised cost by 16%. In combination this would describe an industry where the best performers were pushing the frontier and reducing cost, while other firms were improving, but not quite catching up. In the second period technical change reduced cost by 12% while efficiency change had almost no effect. In carrier detail Table 4, we see that in terms of productivity Alaska Airlines was the top performer, reducing cost by 56% followed closely behind by Spirit, Frontier and Southwest. For several carriers, JetBlue, American, Delta and United, efficiency change added to cost over the period. One potential explanation for this is the series of mergers that occurred between 2010 and 2015[10] and the associated problems consolidating, or "digesting" the acquisitions. In the case of JetBlue, operational struggles in the 2006–2008 period is droving their efficiency based cost increase.

In all periods, change in industry activity level is the most important driver in cost, but there are differences between the periods. In the first period 2002–2009 total costs rose more than activity change, while in the second period 2010–2019 we see the reverse with total costs growing slower than activity. The effects of the pandemic on activity driven cost change is apparent in the sharp drop in 2020 and rebound in 2021–2022. These results are supported by the underlying data which shows average unit cost per passenger mile rising from \$0.125 in 2002 to \$0.135 in 2008, then declining to \$0.109 in 2022.

Although not the focus of our study, we do find evidence supporting the findings of Bitzan and Peoples (2016) who document cost convergence between FSC and LCC. This can be seen in the unit cost results, which show a 7% drop in the standard deviation between carriers, indicating a narrowing of difference.

5.3 Revenue change

Revenue change is presented in the middle section of Tables 3 and 4, like cost the largest driver of change is the level of activity. The effect coming from a change in output attributes is stronger on revenue than on cost, reducing industry revenue by 13% overall. We can observe strategy driven effects in Table 4. For example, the 40% revenue reduction from attribute change for Frontier Airlines can be explained by its conversion to an Ultra-Low-Cost-Carrier (ULCC) in 2014, and accompanying reduction in first class seating and flight frequency. Another example is JetBlue, which positions itself as providing features and benefits not provided by LCCs, but at a lower price than FSC. This differentiation increased cost by 4% over the period but raised revenues by 6%.

[10] In 2005 US Airways merged with America West, in 2009 Northwest and Delta merged; in 2010 Continental joined United; in 2011 Southwest acquired AirTran; in 2013 American and US Airways merged.

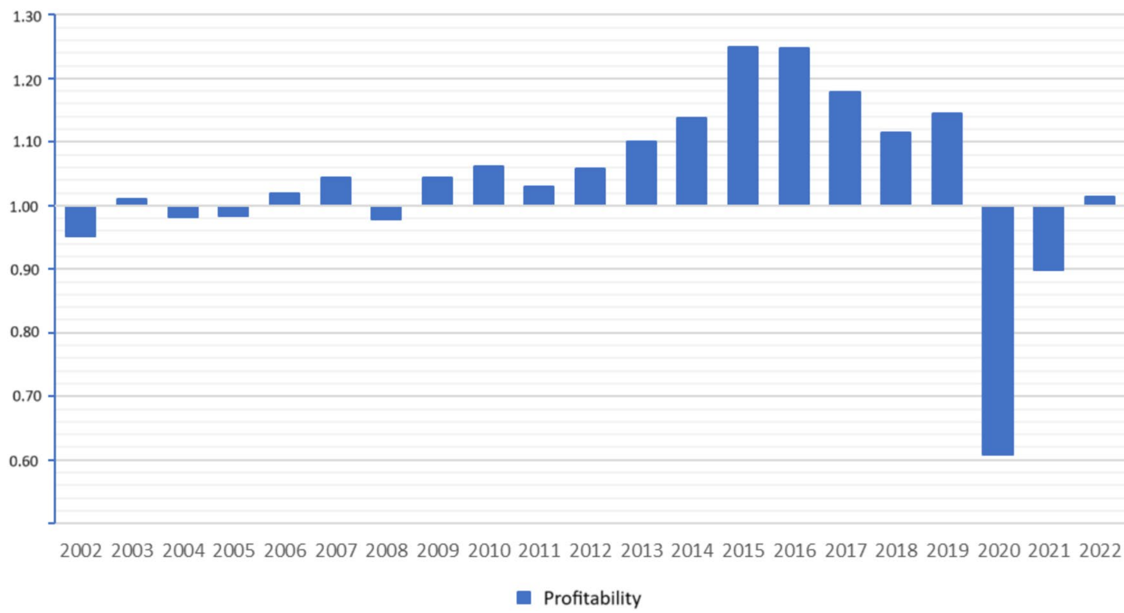


Fig. 6 Annual average profitability

In Table 3 we see that price productivity has added 33% to revenue over the period. Looking deeper, there are macro effects that can be seen in the unpresented annual detail[11]. There is a revenue efficiency decline in 2001–2002 following the September 11th attacks and similar downturn can be seen during the period of the 2007–2009 recession. The addition of baggage fees can be seen in the price productivity measure, an effect that was the subject of research by Brueckner et al. (2015) who found an overall price increase associated with the addition of baggage fees. We see this effect first in 2006 and 2007 in technical change when carriers such as Allegiant and Spirit first introduced baggage fees, and later in 2010 in efficiency change when the practice was widely adopted.

The effect of the 2009–2011 mergers and consolidation can also be seen, first in technical change, and then a few years later in efficiency change as airlines consolidated routes and managed capacity. This was the subject of research by Hazel (2018), who documented that between 2010 and 2014 capacity growth was less than it had been in the past. In the carrier detail both the fee effect and the consolidation effect can be seen in the price productivity driven revenue increases of American, Delta and United.

Overall, input price change reduced revenue by 11%. In the first period 2002–2009 carriers were not able to translate input price driven cost changes into increased prices, seeing a 15% increase in cost, yet a 8% decrease in revenue. In the second period 2010–2019 input prices reduced costs slightly, yet revenues declined more.

Activity was the largest driver of revenue change in the pandemic year of 2020. Dropping revenues slightly more than cost. However, in the post pandemic years 2021–2022, activity change grew revenue growth faster than cost growth.

5.4 Profitability change

In this section we bring together cost and revenue change to explain profitability change as defined inexpression (11). Figure 6 displays annual profitability over the entire period we analyze. In the first period 2002–2009 profitability alternated between years of loss and gain but ending with a profitable 2009. In the second 2010–2019 period, carriers were consistently profitable, peaking at 1.25 in 2015, but then dropping to between 1.11 and 1.18 in the latter half of the period. These results are reflected in the lower part of Table 3 where we see that profitability grew by 9% over period 2002–2009, but then dropped to 6% growth in the period 2010–2019. In Table 3 we see that in both periods attribute change has increased cost more than revenue, resulting in a reduction of profitability. An explanation for this might be found in the research by Bitzan and Peoples (2016) who document convergence of cost, partially driven by attribute change, of FSC and LCC.

In Table 3 we refer to the combined effect of cost and revenue change due to efficiency and technology as "Productivity", however this is not the classical productivity measure. Typically, the contribution of productivity comes as a reduction in required inputs, or an expansion of outputs. In our application, productivity measures two effects, first the cost change due to a reduction in needed inputs,

[11] Full annual results are available on request.

and second a change in the ability of the carrier to convert that output into revenue via higher prices. We refer to this second effect as price productivity. We can observe that productivity adds 67% to profitability overall and that the effect is stronger in the first period. Digging deeper, we see that both cost and revenue technical change contributed strongly to profitability growth in the first period, but in the second period, cost technical change became the primary drive of profitability growth. We discuss the policy implications of this in the next section.

Airline expansion over the entire period drove a growth in cost of 189% and revenue growth of 214%, resulting in profitability growth of 9%. This ratio of activity driven revenue charge over activity driven cost change, can be thought of as the contribution of output mix and input mix changes, as well as the impact of "scale economies" to profitability. The value differs between the two subperiods, reflecting a contribution to profitability in the first period, but almost no change in the second. Input price changes have reduced profitability over the entire period by 30%, almost all of this in the period 2002–2009. This reduction of loss due to input price change, combined with continued productivity growth, is largely the main profitability driver in the second period 2010–2019.

6 Conclusions

This paper decomposes profitability changes in the U.S. airline industry from 2002 to 2022, with a focus on the role of product differentiation. We employ the combination of a cost function and revenue function to explain profitability change, the ratio of the two, in a unique way. We also introduce a novel cost efficiency measure that accounts for output attributes and finds that standard efficiency measures, which exclude product changes and differences between carriers, are biased downward by 5%. These methodological contributions extend the earlier work of C.A.K. Lovell.

Cost decomposition reveals that output attribute changes increased costs by 6%, particularly early in the study. Input prices drove cost surges from 2002 to 2009, contributed to declines from 2010 to 2019, and spiked post-pandemic, underscoring the airline industry's sensitivity to price volatility. Managing these fluctuations demands more resilient cost strategies.

On the revenue side, applying a non-standard revenue function highlighted the impact of attribute changes. Activity effects were the main revenue driver, followed by productivity improvements. Revenue productivity grew by 33%, fueled by technological advancements, baggage fees, and market consolidation. However, degraded service levels from output attribute changes hurt revenue potential, reflecting a less favorable pricing environment. It is worth noting that the low-level positive correlation we found between flight frequency and revenue efficiency should be pointed out as a possible limitation of the applied section, but also opens up avenues for further research on the issue of endogeneity in DEA estimations.

Profitability from 2002 to 2022 was shaped by these shifts. Output attribute changes alone cut profitability by 18%, driven by weaker revenues. Consolidation blurred the lines between low-cost and full-service models, reducing price discrimination and average fares. Technical change in cost and revenue frontiers further boosted profitability through increased market power, raising potential concerns over the reduction of competition. Strategically, airlines must explore ways to pass on input costs or reduce price vulnerability—potentially through capacity cuts and higher fares, though these come with societal and regulatory considerations.

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Declarations

Conflict of interest The authors declare no competing interests.

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