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From Carbon Footprints to Competitive Edges: Analyzing Environmental Efficiency in Aviation*

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ABSTRACT
Purpose: This study conducts a comprehensive analysis of environmental efficiency in the aviation industry, focusing on 19 global airline companies employing diverse business models.
Methodology: Utilizing Data Envelopment Analysis for 2017 to 2022, the research quantifies efficiency levels based on input and output variables, including Fuel Consumption, Revenue Passenger Kilometers, Greenhouse Gas Emissions, and Total Income.
Findings: Noteworthy findings reveal that Alaska Airlines (VRS=1), Lufthansa (VRS=1), Spirit Airlines (VRS=1), and Delta Air Lines (VRS=1) consistently operated at the environmental efficiency frontier, showcasing a proportional relationship between input and output values.
Originality: The dynamic nature of the aviation industry, coupled with the economic implications of environmental initiatives, necessitates a nuanced understanding of airlines' sustainability efforts. Policymakers are urged to consider measures such as the effective introduction of Sustainable Aviation Fuels and large-scale strategies to reduce aviation-related greenhouse gas emissions.
Keywords: Aviation, Environment, Data Envelopment Analysis, Competition, Emissions.
JEL Codes: L53, L93, Q53, Q54.

Karbon Ayak İzinden Rekabet Avantajına: Havacılıkta Çevresel Etkinliğin Analizi

ÖZET
Amaç: Bu çalışma, farklı iş modelleri uygulayan 19 küresel havayolu şirketine odaklanarak, havacılık endüstrisinde çevresel etkinliğin kapsamlı bir analizini yapmayı amaçlamaktadır.
Yöntem: Araştırma, 2017'den 2022'ye kadar Veri Zarflama Analizi'ni kullanarak Yakıt Tüketimi, Ücretli yolcu Kilometresi, Sera Gazı Emisyonları ve Toplam Gelir gibi girdi ve çıktı değişkenlerine dayanarak etkinlik seviyelerini ölçmektedir.
Bulgular: Araştırma Bulguları, Alaska Airlines (VRS = 1), Lufthansa (VRS = 1), Spirit Airlines (VRS = 1) ve Delta Air Lines'ın (VRS = 1) sürekli olarak çevresel etkinlik sınırında faaliyet gösterdiğini ve girdi ve çıktı değerleri arasında orantılı bir ilişki olduğunu ortaya koymaktadır.
Özgünlük: Havacılık endüstrisinin dinamik doğası ve çevresel girişimlerin ekonomik etkileri, havayollarının sürdürülebilirlik çabalarını anlamada daha derinlemesine bir yaklaşıma ihtiyaç duymaktadır. Politika yapıcılara, Sürdürülebilir Havacılık Yakıtlarının etkili bir şekilde tanıtılması ve havacılıkla ilgili sera gazı emisyonlarını azaltmaya yönelik geniş ölçekli stratejiler gibi önlemleri göz önünde bulundurmaları önerilmektedir.
Anahtar Kelimeler: Havacılık, Çevre, Veri Zarflama Analizi, Rekabet, Emisyonlar.
JEL Kodları: L53, L93, Q53, Q54.

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1. INTRODUCTION

As of 2022, aviation accounted for 2% of global energy-related carbon dioxide (CO_2) emissions, with its growth rate surpassing those of rail, road, and shipping in recent decades. Given this impact, the aviation sector recognizes the need for more robust environmental efforts to ensure long-term sustainability. Companies are adopting various measures to enhance environmental responsibility, such as improving energy efficiency, using eco-friendly alternative fuels like biofuels, and operating lower-emission aircraft. According to a study by the International Civil Aviation Organization (ICAO), total greenhouse gas (GHG) emissions from aviation are projected to increase by 400-600% by 2050 compared to 2010 levels (Li and Cui, 2021). This underscores the critical importance of adopting environmentally friendly practices to reduce emissions in the industry. To address this challenge, international organizations like ICAO have introduced regulations targeting GHG emissions from flights. In October 2013, ICAO set a climate goal called Carbon Neutral Growth (CNG2020), which aimed to cap aviation emissions at 2020 levels starting that year (The International Council on Clean Transportation, 2016). ICAO has also established two key objectives for the international aviation sector: achieving a 2% annual improvement in fuel efficiency until 2050 and implementing the CNG2020 initiative from 2020 onward (Cui and Li, 2021; 2017).

Different airlines have implemented various measures to control carbon emissions. The aviation industry can progress toward a more sustainable future by retiring older, less efficient aircraft and optimizing flight capacity utilization (Bravo et al., 2022). Newer aircraft are designed to meet stricter environmental regulations, emit fewer pollutants, and reduce environmental impacts. These advancements improve air quality while supporting sustainability. Additionally, modern fleets incorporate advanced technologies, such as more efficient engines, improved aerodynamics, and lightweight materials, contributing to significant fuel savings and emissions reductions (Isley, 2010:13). For example, China Southern Airlines has taken steps like optimizing its fleet, improving air routes, and installing winglets to enhance fuel efficiency and reduce carbon emissions (China Southern Airlines, 2023:9). Similarly, China Eastern Airlines focuses on fleet optimization, air route improvements, and adopting new technologies to manage carbon emissions (China Eastern Airlines, 2023:8). These initiatives underscore the industry's commitment to environmental sustainability through operational and technological advancements (Cui and Li, 2016). Consequently, environmental efficiency has become as important as operational and financial efficiencies for airlines.

Environmental and sustainability considerations have gained increasing prominence in the aviation industry. There is a growing demand for eco-friendly strategies to reduce pollution, lower emissions, and promote sustainable development (Azuazu et al., 2023). These factors significantly affect competition in the sector, shaping the strategies and decisions of airlines and aviation companies (Baumeister, 2015). Understanding the factors influencing airline performance has become even more critical due to the unexpected challenges posed by the COVID-19 pandemic (Kaya et al., 2023).

This study aims to analyze and compare the environmental efficiency of 19 airline companies operating under different business models. Efficiency levels were measured using the Data Envelopment Analysis (DEA) method from 2017 to 2022. The study also seeks to identify the determinants of environmental efficiency in the aviation sector. It focuses on the 19 airlines with the highest revenue passenger kilometers (RPK), as reported in the International Air Transport Association (IATA) 2021 World Air Transport Statistics (WATS). This approach provides a novel contribution by examining the environmental efficiency of leading global airlines regarding flight frequency and passenger volume. The primary research question is: *How do airline companies with different business models perform in terms of environmental efficiency, and what factors influence this efficiency, especially during the COVID-19 pandemic?*

This study contributes to the literature with several key features. It is one of the most up-to-date global analyses on the subject, covering a broad sample and the 2017-2022 period. Additionally, the study, in addition to some studies addressing the COVID-19 pandemic (Voltes-Dorta et al., 2024; Wu et al., 2024), spans the COVID-19 pandemic, offering insights into the resilience and adaptability of airlines during this unprecedented global crisis. By examining the pandemic's impact on airline efficiency, this research provides actionable insights for airlines, policymakers, and other stakeholders to enhance efficiency and reduce environmental impacts.

The study is structured into five main sections, each focusing on a distinct aspect of the research. The first section provides an introduction, outlining the background, objectives, and significance of the study. The second section presents a comprehensive literature review, discussing relevant theories, previous studies, and key concepts related to the research topic. The third section details the methodology, explaining the research design, data collection methods, and analytical approaches used in the study. The fourth section focuses on the results and discussion, presenting the findings and interpreting them in relation to existing literature. Finally, the fifth section concludes the study by summarizing key insights, highlighting contributions, and suggesting potential directions for future research.

2. LITERATURE REVIEW

The airline industry is increasingly investing in reducing carbon emissions and adopting more environmentally conscious approaches. These efforts require airlines to allocate resources toward solutions such as advanced technologies, biofuels, and more efficient flight methods. Airlines and governments worldwide are now expected to meet new environmental standards, which necessitates assessing the environmental impact of the aircraft in use. To support these efforts, Boeing has developed a tool that evaluates the effectiveness of four key strategies for reducing emissions: modernizing fleets with newer aircraft, improving operational efficiency, utilizing renewable energy, and incorporating future aircraft technologies (BOEING, 2023:14).

In the short and medium term, the widespread adoption of Sustainable Aviation Fuels (SAF), which have a lower carbon intensity than fossil jet fuels, is crucial (Becken et al., 2023). Implementing SAF on a large scale, along with measures to significantly reduce GHG emissions, is essential for achieving meaningful environmental improvements in aviation (Bullerdiek et al., 2021). Reducing traditional aviation fuel (CAF) consumption and transitioning to SAF can play a critical role in mitigating the sector's environmental impact (Capaz et al., 2020; Masum et al., 2023). Shifting from fossil fuels to a renewable energy-driven economy is a major driver for reducing CO_2 emissions and improving air quality (Nieuwenhuijsen, 2020).

Airlines must also develop strategies to minimize cost increases and reduce environmental expenses. These strategies can simultaneously enhance operational efficiency while lowering carbon emissions (Cui et al., 2020). However, the primary focus of businesses remains profit maximization, and emissions reduction initiatives may not always align with this goal. Companies often view environmental responsibilities as additional costs unless accompanied by direct economic benefits or mandated by regulations (Sun et al., 2020). Consequently, these initiatives may not be prioritized.

Customer demand for efficient and low-emission products adds another layer of complexity. The flying public could bear the financial burden of these initiatives, as airlines may pass on additional costs to passengers. Therefore, airlines must carefully analyze and balance the costs of environmental measures with customer pricing.

In response to the pressing issue of aviation carbon emissions, various international organizations and governments have implemented policies and mechanisms to control and reduce emissions (Cui et al., 2020). Airlines have also adopted numerous measures to address this challenge (Cui & Li, 2016). Research by Arter et al. (2022) highlights that emissions during aircraft landing and takeoff significantly impact air quality, further emphasizing the need for comprehensive solutions.

The literature review below summarizes studies that analyze environmental efficiency in the airline industry, highlighting their scope and the input-output variables used. These analyses, primarily using the Data Envelopment Analysis (DEA) method, aim to optimize performance by evaluating environmental, operational, and economic factors. The review outlines various research efforts and methodologies, offering insights into the environmental efficiency of airline companies.

Omrani et al. (2023) examined 16 Iranian airlines in 2019 using a combined DEA and Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) method. Input variables included fleet size (FS), available seat kilometers (ASK), available tonne kilometers (ATK), and the number of employees, while outputs included passenger-kilometers performed, tonne-kilometers performed, and CO_2 emissions. Their three-step methodology identified 11 airlines as sustainably efficient, emphasizing the importance of integrating economic, social, and environmental criteria in performance evaluation. The study demonstrated how combining DEA and TOPSIS provides a robust framework for ranking decision-making units based on multiple criteria. Saini et al. (2023) analyzed U.S. and non-U.S. airlines from 2013 to 2015 using DEA. Inputs included total operating costs, abatement expenses, available seat miles (ASM), and CO_2 emissions, while outputs encompassed net income, operating revenues, ASM, revenue passenger miles (RPM), and CO_2 emissions. The study highlighted the significance of environmental abatement efforts in determining airline efficiency, showcasing DEA as a comprehensive evaluation tool compared to methods like regression analysis. Liu et al. (2020) applied a two-stage DEA model to analyze 15 global airlines from 2011 to 2017. Inputs included ASK, fleet size (FS), and transportation revenue, while outputs were revenue passenger kilometers (RPK) and greenhouse gas (GHG) emissions. The study demonstrated how managing load capacity efficiently could reduce carbon emissions, highlighting the relationship between operational load and environmental performance. Ali and See (2023) employed the Enhanced Hyperbolic Distance Function (EHDF) methodology to analyze 112 global airlines in 2017. Inputs were fuel, other operating inputs, and capital, while outputs included ATK and CO_2 emissions. Their findings indicated that airline alliances and higher weight load factors improve environmental efficiency. The EHDF model provided a nuanced assessment by simultaneously expanding desirable outputs and contracting undesirable outputs and inputs. Pereira and Mello (2021) evaluated three Brazilian airlines during 2019-2020 using the Multiple Criteria-DEA (MCDEA) approach. Inputs included the number of takeoffs, ATK, and fuel consumption (FC), while the sole output was revenue tonne kilometers (RTK). The study found that newer aircraft fleets contributed to fuel savings and reduced emissions, improving environmental efficiency. The MCDEA approach enabled a detailed examination of efficiency, particularly in the context of external shocks like the COVID-19 pandemic. Kim and Son (2021) analyzed 31 global airlines from 2014 to 2018 using DEA. Inputs included FC, operating costs, number of employees, and FS, while outputs comprised total revenue, RPK, RTK, passenger load factor, cargo load factor, and CO_2 reduction. The study highlighted the role of EU environmental regulations, such as the European Emissions Trading Scheme, in driving improvements in environmental efficiency, especially among European and Russian airlines. Peoples et al. (2020) employed the DEA-Malmquist Productivity Index (MPI) to study 17 Asia-Pacific airlines between 2003 and 2011. Inputs included FS, FC, and employee numbers, with outputs being RPK and operating revenue. The study underscored the importance of fuel efficiency and collaboration between airlines to optimize routes, reduce fuel consumption, and enhance sustainability. Li et al. (2015) applied the Virtual Frontier Network Slacks-Based Measure (SBM) method to 22 international airlines from 2008 to 2012. Inputs included employee numbers, aviation kerosene, ATK, ASK, FS, RTK, RPK, and sales costs. Outputs comprised ATK, ASK, RTK, RPK, and total business income. The study offered a comprehensive evaluation of airline efficiency across operational, service, and sales stages. Gramani (2012) analyzed 34 Brazilian and American airlines from 1997 to 2006 using a two-phase DEA approach. Inputs included aircraft fuel, wages, benefits, and costs per ASM, while outputs were RPK, flight revenue, and flight income. The study emphasized the interplay between operational efficiency, financial performance, and resource optimization in improving environmental sustainability. Lu et al. (2012) examined 30 U.S. airlines in 2006 using a two-stage DEA approach. Inputs included employees, FC, total seats, and maintenance costs, while outputs encompassed ASM, ATM, RPM, and non-passenger revenue. The study revealed that low-cost carriers excelled in production efficiency, whereas full-service carriers outperformed in marketing efficiency. Chiou and Chen (2006) used DEA combined with Tobit regression to evaluate a Taiwanese airline in 2001. Inputs were fuel cost, personnel cost, aircraft cost, number of flights, and seat miles, while outputs included flights, seat miles, passenger miles, and embarkation passengers. The analysis emphasized the importance of cost efficiency, service effectiveness, and operational sustainability. Asker (2018) analyzed 16 traditional airlines using DEA. Inputs included ASK, seat capacity, employee numbers, and fuel costs, while outputs were RPK, load factor, and total passengers. The study highlighted differences in efficiency models, with the input-output-focused BCC model offering distinct insights compared to the CCR model. Tanrıverdi et al. (2023) investigated the multi-dimensional impacts of COVID-19 on the sustainability performance of 56 airlines (2017–2021) using a MEREC–CoCoSo/Borda model. The study revealed that while decarbonization lost prominence in 2020, it regained importance during the "new normal" as the industry recovered.

The literature review highlights the urgent need for the airline industry to enhance its environmental efficiency, given the escalating carbon emissions associated with aviation. It underscores the importance of investing in innovative solutions, such as advanced technologies, biofuels, and optimized flight methods, to mitigate the environmental impact of air travel. However, the economic challenges posed by these initiatives necessitate strategic approaches to manage costs, enabling airlines to embrace environmental responsibility without compromising operational efficiency. Despite the inherently profit-driven nature of the industry, aligning environmental initiatives with economic benefits and regulatory compliance is essential to achieving industry-wide commitment. References to international policies and mechanisms regulating aviation emissions further emphasize the global acknowledgment of this critical issue. The reviewed studies, which explore emissions and their impact on air quality, provide a strong foundation for our research. The alignment between our study’s input and output variables and those examined in the literature strengthens the relevance and importance of our investigation into environmental efficiency in aviation. This positions our research as a vital contribution to understanding how airlines can achieve competitive advantages while addressing the pressing challenge of carbon footprints.

Our study also introduces key distinctions. While many prior studies focused on regional airlines or specific time frames, we adopt a broader, global perspective by analyzing airlines with diverse business models over a six-year period. Our research encompasses the COVID-19 pandemic, offering insights into how this unprecedented crisis influenced airline efficiency. This approach enables us to evaluate the resilience and adaptability of airlines during and after the pandemic, which represents a significant departure from the pre-pandemic focus of most prior research. By addressing competitive advantages linked to environmental performance during this transformative period, our study provides a comprehensive understanding of the factors shaping environmental efficiency, setting it apart in both scope and depth.

3. METHODOLOGY

The method used in this study is the DEA model, as developed by Charnes et al. (Charnes et al., 1978). DEA is a non-parametric method used to evaluate the relative efficiency of Decision-Making Units (DMUs) by comparing their inputs and outputs (Scheraga, 2004). At the same time, the DEA method minimizes input usage while identifying the most efficient input and output combinations within a set of observations known as DMUs. The DEA model compares the efficiency of DMUs by constructing an efficiency frontier based on the best-performing units, known as the efficient frontier or production possibility set. Each DMU is assigned an efficiency score between 0 and 1, where 1 represents perfect efficiency. The efficient frontier represents the boundary of attainable efficiencies based on the best-performing DMUs (Førsund & Sarafoglou, 2002).

In the study, efficiency performance analysis was conducted using an input-oriented Banker, Charnes, and Cooper (BCC) model under the Variable Returns to Scale (VRS) assumption through DEA with input and output variables related to 19 airline companies. Banker, Charnes, and Cooper developed the BCC model to evaluate efficiency under the assumption of variable returns to scale by adding the constraint $\sum_{j=1}^{m} \lambda j = 1$ to the Charnes, Cooper, and Rhodes (CCR) model (Cooper et al., 2011:51-55).

Based on identified inputs and outputs, the DEA models were analyzed using the DEA Solver 3.0 package program, an add-in for Microsoft Excel. Calculations for technical efficiency - VRS efficiency scores were performed using the DEA method in the study. Technical efficiency represents the firm's ability to maximize output with given inputs or produce the same output level while minimizing inputs (Cooper et al., 2007:83). In this regard, the study analyzed the data of 19 airlines with the highest RPK according to the IATA 2021 WATS report over 6 years (2017-2022) using the DEA method, obtaining environmental efficiency scores for the airlines.

The process of selecting inputs and outputs using the DEA technique significantly affects the reliability of the analysis. There is no consensus on selecting appropriate input and output variables for evaluating the performance of airline companies (Nissi and Rapposelli, 2008:271). In this regard, the input and output variables chosen to have been selected from among those most commonly used in the literature and that best reflect environmental performance from environmental perspectives.

Table 1. Environmental efficiency input and output variables and data sources

Type	*Variables*	*Source*
Inputs	FC	Collected individually from the annual reports of airlines
	RPK	Collected individually from the annual reports of airlines
Outputs	GHG Emission (GHG)	Collected individually from the annual reports of airlines
	Total Income (TI)	Collected individually from the annual reports of airlines

FC: Fuel consumption is a critical variable in assessing airline environmental efficiency. It directly correlates with the environmental impact of airline operations, as higher fuel consumption typically results in higher greenhouse gas emissions. Lower fuel consumption for a given level of output (measured in RPK) suggests higher efficiency. Conversely, high fuel consumption indicates inefficiencies in operations and potential areas for environmental performance improvement.

RPK: RPK is a standard industry measure that reflects the volume of passenger traffic. This metric is critical for understanding the scale of airline operations and their corresponding environmental impact. High RPK values with efficient fuel use and low emissions indicate high operational and environmental efficiency.

GHG Emissions: GHG emissions directly measure the environmental impact of an airline's operations. High emissions, even with high RPK values, suggest that the airline needs to improve its fuel efficiency and adopt greener technologies or practices.

TI: Total income is a financial performance indicator that reflects an airline's revenue-generating ability. If high income is associated with high GHG and FC, it suggests that the airline's revenue generation is not environmentally sustainable.

DEA is a mathematical model used to measure the efficiency of a set of DMUs with multiple inputs and outputs. In this study, the BCC model was used, aiming to minimize the input quantities while maintaining the current output level. Accordingly, assuming that the 19 homogeneous DMUs (DMUj, $j = 1, \ldots .19$) produce two outputs y_{rj} ($r = 1,2$) based on two inputs x_{ij} ($i = 1,2$) and considering that the vectors x_j = x_{1j}, x_{2j}) and y_j = (x_{1j}, x_{2j}) are positive and non-zero vectors, the mathematical model of the study is formulated to represent the relationship between inputs and outputs.

Accordingly, the model is expressed as follows:

Minimize = θ_k

Subject to:

$\sum_{j=1}^{19} y_{rj}\,\lambda_j \geq Y_{r0} \qquad r = 1, 2 \qquad (1)$

$\sum_{j=1}^{19} x_{ij}\lambda_j \leq \theta_k x_{i0} \qquad i = 1, 2 \qquad (2)$

$\sum_{j=1}^{19} y_j\lambda_j = 1 \qquad (3)$

$\lambda_j \geq 0, \qquad j = 1, \dots \dots 19 \qquad (4)$

where θ_k is the efficiency score of DMU k, x_{i0} and y_{r0} are the inputs and outputs of the DMU being evaluated (DMU0), λ_j are the weights assigned to each DMU in the reference set. In this model, x_1, x_2 are the inputs (FC and RPK, respectively) and y_1, y_2 are the outputs (GHG and TI, respectively). The aim is to minimize θ_k such that the DMU under evaluation operates efficiently relative to the others.

Undesirable outputs such as GHG are inevitably generated in the ordinary course of production processes. This divergence from the traditional DEA efficiency model's 'maximize outputs' hypothesis necessitates a specialized consideration of undesirable outputs for the extension of the conventional DEA efficiency model (Song et al., 2012). As a result, the undesirable output variable, GHG emissions, was inverted (1/ GHG) for use in the DEA, recognizing its opposite nature within the analysis framework. Over six years, from 2017 to 2022, the descriptive statistics for environmental variables, as seen in Table 2, unveil noteworthy patterns in the aviation industry.

Table 2. Descriptive statistics of the environmental variables

Year	*Variables*	*Max*	*Min*	*Mean*	*Std. Dev.*
2017	*Environmental Inputs*				
	FC (000 lt)	11,250,372	459,472	5,238,945	2,904,453
	RPK(000)	364,268,577	39,598,733	196,470,721	98,694,161
	Environmental Outputs				
	GHG (tonne)	36,078,118	3,300,799	19,837,976	10,614,828
	TI (000$)	42,622,000	2,643,552	19,180,888	12,891,567
2018	*Environmental Inputs*				
	FC (000 lt)	11,580,308	551,106	5,562,326	3,038,261
	RPK(000)	372,015,959	49,283,551	209,364,773	101,506,741
	Environmental Outputs				
	GHG (tonne)	37,301,128	3,959,088	20,818,983	10,791,786
	TI (000$)	44,541,000	3,323,034	20,762,059	13,569,693
2019	*Environmental Inputs*				
	FC (000 lt)	10,879,616	629,554	5,639,049	3,085,231
	RPK(000)	388,257,458	56,721,787	218,656,920	104,212,423
	Environmental Outputs				
	GHG (tonne)	38,452,620	4,522,648	21,377,143	10,635,849
	TI (000$)	47,007,000	3,830,536	21,075,545	13,751,190
2020	*Environmental Inputs*				
	FC (000 lt)	6,132,700	386,873	2,747,883	1,533,236
	RPK(000)	153,440,110	28,400,000	74,027,080	40,189,926
	Environmental Outputs				
	GHG (tonne)	19,831,000	2,779,254	10,371,490	5,592,603
	TI (000$)	17,337,000	1,810,022	8,421,160	5,277,996
2021	*Environmental Inputs*				
	FC (000 lt)	6,053,100	581,743	3,533,501	1,729,074
	RPK(000)	259,970,211	30,700,000	111,656,940	61,029,190
	Environmental Outputs				
	GHG (tonne)	28,810,000	4,240,868	13,554,296	6,919,141
	TI (000$)	29,899,000	3,230,775	12,791,591	8,292,359
2022	*Environmental Inputs*				
	FC (000 lt)	8,463,363	704,884	4,406,577	2,269,422
	RPK(000)	347,013,190	60,354,570	160,683,183	92,194,561
	Environmental Outputs				
	GHG (tonne)	34,629,000	5,934,669	16,272,958	9,072,672
	TI (000$)	50,582,000	3,873,728	19,498,860	14,963,654

In terms of environmental inputs in Table 3, the maximum FC ranged from 6,132,700 thousand liters in 2020 to 11,580,308 thousand liters in 2018, reflecting fluctuations in fuel usage across these years. Similarly, RPK showed considerable variability, reaching its zenith in 2018 at 372,015,959 thousand kilometers and hitting its lowest point in 2020 at 153,440,110 thousand kilometers. These trends suggest dynamic shifts in operational aspects and passenger demand within the aviation sector.

Regarding environmental outcomes, GHG measured in tonnes increased steadily from 2017 to 2019, peaking in the second year at 38,452,620 tonnes. However, as also emphasized in Ang et al.'s (Ang et al., 2023) study, it was found to be at its lowest level in 2020 due to the impact of the COVID-19 Pandemic. Meanwhile, TI, expressed in thousands of dollars, displayed a fluctuating pattern, with the highest recorded value in 2022 at $50,582,000. These variations in income suggest external factors influencing airlines' financial performance throughout the analyzed period.

4. RESULTS and DISCUSSION

Table 3 presents the return efficiencies of DMUs with respect to environmental scale, both annually and as 6-year averages.

Table 3 Environmental efficiency scores of the airlines between 2017-2022

DMU	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*Average*
Alaska Airlines	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Lufthansa	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Spirit Airlines	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Delta Air Lines	0.993	1.000	1.000	1.000	1.000	1.000	1.000
JetBlue	0.976	0.998	0.990	1.000	0.930	0.946	0.973
American Airlines	1.000	1.000	0.967	1.000	0.927	0.878	0.962
Southwest Airlines	0.978	0.984	0.935	0.831	0.909	0.853	0.915
United Airlines	0.923	0.922	1.000	0.888	0.866	0.849	0.908
British Airways	0.798	0.883	0.913	0.753	1.000	0.915	0.877
IndiGo	0.809	0.780	0.785	0.980	0.998	0.716	0.845
Air France + KLM	0.792	0.853	0.865	0.705	0.769	0.743	0.788
Emirates	0.590	0.638	0.675	1.000	0.794	0.781	0.746
LATAM	0.726	0.774	0.799	0.688	0.613	0.798	0.733
Ryanair	0.704	0.734	0.592	0.961	0.650	0.558	0.700
Turkish Airlines	0.647	0.719	0.768	0.675	0.610	0.753	0.696
Air China	0.646	0.703	0.685	0.476	0.576	1.000	0.681
China Eastern Airlines	0.616	0.670	0.656	0.436	0.516	1.000	0.649
China Southern Airlines	0.588	0.623	0.621	0.456	0.539	0.852	0.613
Aeroflot Russian Airlines	0.598	0.617	0.639	0.471	0.521	0.640	0.581

As seen in Table 3, Alaska Airlines, Lufthansa, Spirit Airlines, and Delta Air Lines consistently achieved high-efficiency scores, operating at the environmental efficiency frontier throughout the examined periods. Notably, three of these DMUs are American companies, while Lufthansa Airlines stands out as the sole European representative in the ranking. These efficiency scores can be attributed to rigorous cost management strategies, including fuel-saving initiatives, the use of fuel-efficient aircraft, and operational optimizations aimed at minimizing unnecessary fuel consumption and emissions. Spirit Airlines, in particular, demonstrated exceptional performance with the lowest FC input and GHG and TI output values across all periods. This analysis underscores the DEA principle of emphasizing proportional relationships between input and output values rather than their absolute quantities, positioning these DMUs as industry leaders in environmental performance and granting them a competitive advantage.

Following these top performers, JetBlue Airways and American Airlines emerged as two distinct American companies with closely matched overall efficiency averages. JetBlue achieved a full efficiency score (VRS=1) in 2020, supported by its investments in newer, fuel-efficient aircraft and its commitment to carbon neutrality for domestic flights. Although American Airlines recorded relatively lower efficiency scores in 2020, it ranked 6th overall. The company faced challenges with the highest GHG output among DMUs in 2020 and 2021, highlighting the necessity for policies aimed at reducing emissions. However, American Airlines' sustainability initiatives, such as investing in fuel-efficient planes and adopting SAF, have helped improve its environmental performance.

United Airlines reached the efficiency frontier only in 2019 but ranked 8th overall, with a VRS of 0.908. Its Eco-Skies program, which focuses on reducing fuel consumption, minimizing waste, and adopting sustainable practices, has contributed to its commendable efficiency scores. British Airways demonstrated significant improvement in environmental efficiency, achieving the efficiency frontier in 2021 and maintaining an upward trend after recording its lowest score in 2020. The airline's long-term commitment to achieving net-zero carbon emissions by 2050 and adopting more efficient aircraft and SAF has played a pivotal role in this recovery, earning it a 9th-place ranking overall. Emirates, another notable performer, achieved efficiency frontier status only in 2020. Although it recorded lower efficiency scores in other years, the company improved its environmental performance in 2020 and 2021 by reducing FC. Emirates ranked 12th overall, with a VRS score of 0.746, reflecting its increased competitiveness in environmental efficiency.

In 2022, the efficiency scores of various airlines provided insights into their relative performance. Alaska Airlines, Lufthansa, Spirit Airlines, and Delta Air Lines all achieved total efficiency scores (VRS=1), indicating optimal input-output relationships. JetBlue Airways continued its trend of high efficiency with a score of 0.946, maintaining its competitive position. American Airlines demonstrated improvement with a score of 0.878, while Southwest Airlines (0.853) and United Airlines (0.849) also showcased efficient operations. British Airways sustained its efficiency frontier status from the previous year, recording a score of 0.915, further solidifying its competitive edge. Other airlines, such as Air France + KLM and IndiGo, achieved commendable efficiency scores through fleet renewal, improved operations, and waste reduction initiatives.

Despite these successes, some airlines faced challenges. Ryanair recorded a decrease in efficiency with a score of 0.558, signaling areas for potential improvement. Similarly, Aeroflot Russian Airlines faced challenges in optimizing its inputs and outputs, achieving a score of 0.640. These fluctuations underscore the dynamic nature of the aviation sector and the importance of ongoing strategic adjustments to enhance overall efficiency and maintain competitiveness.

The impact of the COVID-19 pandemic on the aviation industry is evident in the efficiency scores for 2020 and 2021, as illustrated in Figure 1. Many airlines experienced a decrease in efficiency during this period, reflecting the severe disruptions caused by the pandemic. However, a recovery trend emerged in 2022, highlighting the resilience and adaptability of the industry. This analysis demonstrates that efficiency improvements are not solely statistical outcomes but the result of deliberate and sustained efforts to enhance environmental performance. By adopting innovative practices and aligning operational objectives with sustainability goals, leading airlines have demonstrated their ability to achieve competitive advantages while addressing critical environmental challenges.

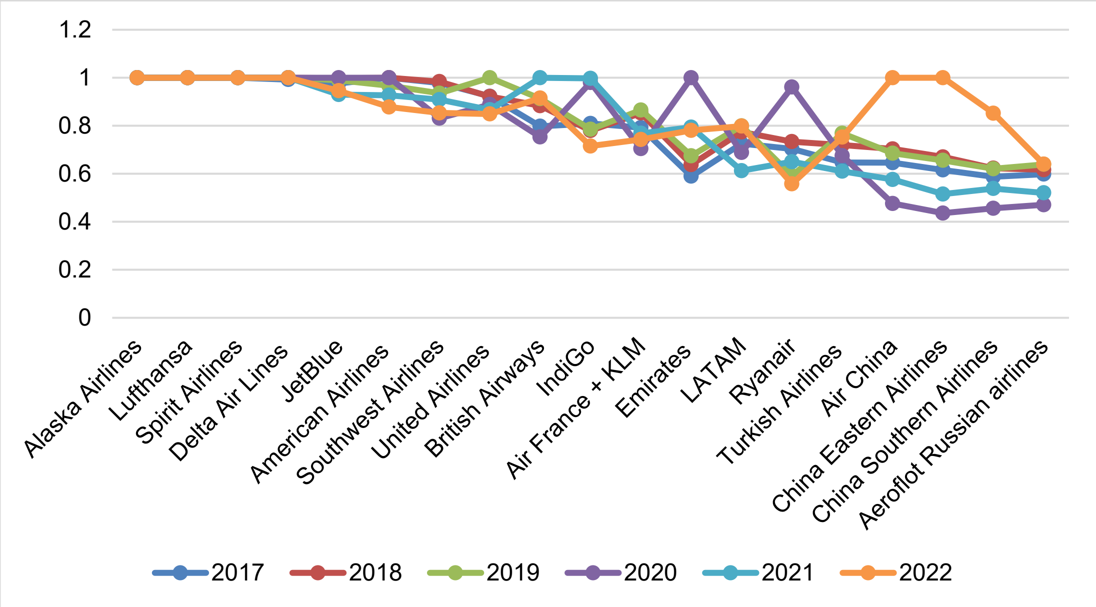

Figure 1. Environmental efficiency scores of the airlines between 2017-2022

JetBlue, American Airlines, Southwest Airlines, and United Airlines all showed a slight decline in efficiency from 2021 to 2022. This could be attributed to the lingering effects of the COVID-19 Pandemic, such as reduced travel demand and operational disruptions. Despite this, these airlines maintained relatively high-efficiency scores, indicating resilience and adaptability in the face of adversity. British Airways, IndiGo, Air France + KLM, Emirates, LATAM, Ryanair, Turkish Airlines, and Aeroflot Russian Airlines demonstrated varying degrees of improvement in efficiency from 2021 to 2022. This positive trend suggests that these airlines successfully adjusted their strategies and operations to navigate the challenges posed by the COVID-19 Pandemic, optimizing their performance. Notably, Air China, China Eastern Airlines, and China Southern Airlines, which had lower efficiency scores in 2021, experienced a significant improvement in

2022. This could be indicative of the recovery of the aviation industry in the Asia-Pacific region as travel restrictions eased and demand began to rebound. Overall, the comparison between 2021 and 2022 efficiency scores underscores the resilience and adaptability of airlines in the face of the COVID-19 Pandemic. While challenges persisted, many airlines demonstrated the ability to enhance their efficiency and operational effectiveness, paving the way for recovery in the post-pandemic era.

Table 4 provides potential improvements that airlines can implement based on underutilized capacities (UC) in their inputs, along with high-density DMUs that can serve as references for these enhancements for the year 2022.

Table 4. 2022 potential improvement for each airline

				FC		*RPK*	
No	*DMU*	*Score*	*Reference*	*UC*	*Diff. (%)*	*UC*	*Diff. (%)*
1	Delta Air Lines	1	-	0	0	0	0
2	China Eastern Airlines	1	-	0	0	0	0
3	Air China	1	-	0	0	0	0
4	Lufthansa	1	-	0	0	0	0
5	Spirit Airlines	1	-	0	0	0	0
6	Alaska Airlines	1	-	0	0	0	0
7	JetBlue	0.946	Lufthansa (0.79)	61,239	-5	4,601,343	-5
8	British Airways	0.915	Air China (1)	441,979	-8	8,863,625	-8
9	American Airlines	0.878	Alaska Airlines (0.954)	636,073	-12	42,326,164	-12
10	Southwest Airlines	0.853	China Eastern Airlines (0.395)	376,863	-15	36,407,676	-18
11	China Southern Airlines	0.852	Lufthansa (0.604)	670,093	-15	15,088,357	-15
12	United Airlines	0.849	Air China (0.781)	728,211	-15	50,246,209	-15
13	LATAM	0.798	Air China (0.422)	1,292,200	-23	18,670,919	-20
14	Emirates	0.781	Spirit Airlines (0.553)	1,855,225	-22	49,511,535	-22
15	Turkish Airlines	0.753	Lufthansa (1)	1,396,664	-25	40,188,980	-25
16	Air France + KLM	0.743	Spirit Airlines (0.618)	1,826,214	-26	52,902,352	-26
17	IndiGo	0.716	Alaska Airlines (0.868)	5,938,769	-78	26,714,472	-28
18	Aeroflot Russian Airlines	0.640	Spirit Airlines (1)	912,206	-36	35,429,677	-36
19	Ryanair	0.558	Alaska Airlines (1)	877,115	-44	120,255,508	-56

Table 4 presents an overview of FC and RPK for each airline, along with corresponding scores and references. Delta Air Lines, China Eastern Airlines, Air China, Lufthansa, Spirit Airlines, and Alaska Airlines show no suggested improvements, indicating optimal utilization. Noteworthy recommendations include JetBlue considering a 5% reduction in FC and a 5% decrease in the RPK concerning Lufthansa. British Airways, American Airlines, and Southwest Airlines are advised to explore enhancements with 8%, 12%, and 15% reductions, respectively, in both FC and RPKs, referencing Air China, Alaska Airlines, and China Eastern Airlines. United Airlines, China Southern Airlines, LATAM, Emirates, Turkish Airlines, Air France + KLM, IndiGo, Aeroflot Russian Airlines, and Ryanair are also encouraged to make substantial improvements, tailoring reductions in FC and RPK based on their respective reference airlines. IndiGo stands out with a notable 78% reduction in FC and a 28% decrease in the RPK, referencing Alaska Airlines. With the most significant potential for improvement, Ryanair is advised to explore a 44% reduction in FC and a substantial 56% decrease in the RPK, taking Alaska Airlines as a reference. These recommendations aim to guide airlines towards optimizing their operations and enhancing efficiency in the competitive aviation landscape.

The table highlights the areas where each airline can improve, emphasizing the differences in resource utilization. By addressing these UCs, airlines can optimize their operations and enhance overall efficiency, ultimately contributing to a more robust and competitive industry performance. Similarly to Liu et al. 2020's work, improving energy efficiency—whether through optimized operations or newer technologies—is a dominant factor in reducing emissions and enhancing sustainability.

5. CONCLUSION

Environmental issues, as in other sectors, form a significant agenda item for the aviation industry. Governments and international organizations closely monitor environmental outputs, applying stringent sanctions to ensure the sustainable use of resources. Consequently, analyzing and disclosing airline companies' environmental activities is crucial. This study employs FC and RPK as input variables for environmental efficiency analysis, while GHG and TI serve as output variables. Given the nature of DEA, which emphasizes minimizing inputs and maximizing outputs, high GHG levels are deemed undesirable. A low GHG output increases the efficiency of a DMU, and thus GHG is analyzed in an inverted manner.

Under the BCC model, created with the VRS assumption for scale variation between 2017-2022, airlines like Alaska Airlines, Lufthansa, and Spirit Airlines consistently operated at the efficiency frontier. Delta Air Lines, with a performance score of VRS = 0.99 in 2017 and VRS = 1 in subsequent years, also achieved full efficiency and can be considered among the top performers. JetBlue Airways, American Airlines, Southwest Airlines, United Airlines, IndiGo, and British Airways operated at the efficiency frontier in certain years while performing inefficiently in others. With overall scores above the average, these DMUs demonstrate a competitive edge in environmental efficiency.

In contrast, airlines such as Air France + KLM, Emirates, Ryanair, LATAM, Turkish Airlines, Air China, China Eastern Airlines, Aeroflot Russian Airlines, and China Southern Airlines displayed lower overall efficiency scores. Among these, Emirates reached the efficiency frontier only in 2020, while others failed to do so in any year. Despite being operationally effective, Ryanair and LATAM have low scores in the environmental category. Aeroflot, the only Russian DMU in the study, performed poorly, while Chinese-origin DMUs also recorded notably weak efficiency scores. This aligns with findings by Liu et al. (2020), which highlight the higher energy efficiency of European and American airlines compared to their Asian counterparts.

Chinese airlines face unique challenges, operating in a highly competitive domestic environment. Unlike airlines in the U.S. and Europe, Chinese carriers have limited influence in international markets, where international travel constitutes a smaller share of their operations (Wang et al., 2019). China's aviation industry, shaped by its historically protectionist structure and strict regulations, operated under military control until 1979 (Cao et al., 2015). Despite significant investments, rapid growth and heavy traffic pressures have hindered environmental efficiency in China's aviation sector (Fu et al., 2020). Greater market liberalization and deregulation could improve domestic companies' performance (Su et al., 2020).

The analysis also reveals operational distinctions between low-cost carriers (LCCs) and full-service carriers (FSCs). LCCs like Spirit Airlines, Southwest, and Ryanair benefit from streamlined operations that emphasize cost reduction and often yield better environmental efficiency. Conversely, FSCs such as American Airlines and British Airways, and state-owned carriers like those from China and Russia, face challenges in balancing complex service offerings with sustainability goals. Hybrid models, such as LATAM, often struggle to achieve efficiency, particularly when sustainability is not prioritized.

Policymakers should focus on measures to enhance environmental efficiency, including optimizing air traffic, revising flight routes, and investing in energy-saving technologies. Airlines must prioritize retiring older, less fuel-efficient aircraft and transitioning to SAF to reduce GHG emissions. Increasing the load factor is another critical strategy, as it maximizes flight efficiency and reduces emissions per passenger (Isley, 2010:16). Liu et al. (2020) emphasize that shifting from traditional fossil fuels to SAF is vital for lowering carbon footprints in the sector.

For future studies, a longer longitudinal analysis is recommended to assess factors like passenger load and fuel types on environmental efficiency. Incorporating airlines from diverse regions and engaging stakeholders—including policymakers, airline representatives, and passengers—will provide a more comprehensive perspective on challenges and opportunities. Additionally, exploring emerging technologies, conducting in-depth economic analyses, and evaluating current policies will contribute to a holistic understanding of sustainability practices in aviation.

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