EVALUATING OPERATIONAL PERFORMANCE, ENERGY AND CO$_2$ EFFICIENCY AND COST OF POLLUTION OF AIRLINES USING NETWORK DEA APPROACH

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LIST OF ABBREVIATIONS

ACTK	Available Cargo Tonne Kilometers
AE	Allocation Efficiency
ASK	Available Seat Kilometers
ATK	Available Tonne Kilometers
ATM	Air Traffic Management
CRS	Constant Returns to Scale
CORSIA	Carbon Offsetting and Reduction Scheme For International Aviation
CTK	Cargo Tonne Kilometers
DEA	Data Envelopment Analysis
DDF	Directional Distance Function
DMU	Decision Making Unit
DNDEA	Dynamic Network Data Envelopment Analysis
EBIT	Earnings Before Interest and Taxes
EU-ETS	European Union Emissions Trading System
FSC	Full-Service Carrier
FTK	Freight Tonne Kilometers
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
ICP	Internal Carbon Pricing
IDF	Input-Oriented Distance Function
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LPI	Logistics Performance Index
MAC	Marginal Abatement Cost
MTOW	Maximum Take-Off Weigh
MTR	Meta-Technology Ratio
NDEA	Network DEA
OAG	Official Airline Guide
ODF	Output-Oriented Distance Function
OPEX	Operation Expense

PPS	Production Possibility Set
RFK	Revenue Freight Kilometers
RAM	Range-Adjusted Measure
RPK	Revenue Passenger Kilometers
RM	Russell Measure
SAF	Sustainable Aviation Fuels
SBM	Slacks-Based Measure
SDG	Sustainable Development Goal
SFA	Stochastic Frontier Analysis
SP	Shadow Price
TE	Technical Efficiency
TFP	Total Factor Productivity
TGR	Technology Gap Ratio
UE	Unified Efficiency
UN	United Nation
VRS	Variable Returns to Scale

MENILAI PRESTASI OPERASI, KECEKAPAN TENAGA DAN CO_2 DAN KOS PENCEMARAN BAGI SYARIKAT PENERBANGAN MENGGUNAKAN PENDEKATAN DEA RANGKAIAN

ABSTRAK

Industri penerbangan hanya boleh mencapai pembangunan mampan jika ia memastikan pembangunan ekonomi dan mengawal pencemaran alam sekitar. Walau bagaimanapun, industri penerbangan menghadapi cabaran besar terhadap kemampanannya kerana permintaan untuk pengangkutan adalah kukuh, tetapi keuntungan adalah rendah dan disertai dengan peningkatan mendadak dalam output yang tidak diingini. Cara syarikat penerbangan boleh menggunakan sumber input dengan lebih cekap, memaksimumkan output yang diingini, mengurangkan output yang tidak diingini dan beroperasi dengan cekap adalah isu yang mendesak untuk penyelidikan. Tesis ini menangani masalah penyelidikan ini menggunakan Data Envelopment Analysis (DEA), yang digunakan secara meluas untuk penilaian kecekapan kerana keupayaannya untuk mengendalikan pelbagai input dan output tanpa memerlukan andaian priori pada bentuk fungsian. Memandangkan kepelbagaian teknologi syarikat penerbangan yang berbeza dari segi struktur operasi mereka (sama ada mereka mengambil bahagian dalam pakatan strategik dinamik atau tidak), tesis ini mula-mula membina model analisis sampul data rangkaian dinamik kesatuan (DNDEA) di bawah rangka kerja metafrontier untuk menilai prestasi operasi dinamik 24 syarikat penerbangan global dari 2017 hingga 2019 didapati bahawa kecekapan keseluruhan kumpulan metadinamik adalah. jauh lebih tinggi daripada kumpulan bukan perikatan. Ini menunjukkan bahawa menyertai pakatan strategik boleh memberi kesan positif kepada prestasi operasi syarikat penerbangan. DNDEA boleh memberikan gambaran yang komprehensif dan dinamik tentang kecekapan operasi syarikat penerbangan dari semasa ke semasa, membantu syarikat penerbangan dan penggubal dasar untuk mengoptimumkan peruntukan sumber dengan lebih baik dan mencapai pembangunan mampan. Seterusnya, model analisis sampul data rangkaian pengukuran terlaras julat (RAM-NDEA) telah dibina di bawah rangka kerja metafrontier untuk menilai skor kecekapan bersatu, tenaga dan CO_2 untuk 59 syarikat penerbangan global pada tahun 2019 di bawah pelupusan semula jadi, pelupusan pengurusan dan penyatuan dua konsep boleh guna. Keputusan empirikal menunjukkan bahawa kecekapan keseluruhan bersatu kumpulan pakatan adalah lebih besar daripada kumpulan bukan perikatan di bawah ketiga-tiga langkah UE, dan kecekapan tenaga dan CO_2 kumpulan perikatan adalah lebih besar daripada kumpulan bukan perikatan di bawah pelupusan pengurusan dan dua konsep pelupusan, yang menunjukkan bahawa menyertai pakatan adalah kondusif untuk meningkatkan prestasi syarikat penerbangan dan penyatuan. Di samping itu, interaksi positif kebolehgunaan semula jadi dan pengurusan pada kecekapan bersatu didapati untuk kebanyakan syarikat penerbangan. Ini menunjukkan kelebihan langkah kecekapan bersatu dan kebolehlaksanaan untuk mencapai pembangunan mampan dengan mengimbangi peningkatan prestasi operasi dan alam sekitar. Akhir sekali, tesis ini membina model dwi fungsi jarak arah bukan jejarian (NDDF) dan mengira kos pengurangan marginal (MAC) CO_2 untuk 59 syarikat penerbangan global pada 2019 untuk memahami potensi pengurangan syarikat penerbangan. Keputusan menunjukkan bahawa purata MAC kumpulan perikatan adalah lebih besar daripada kumpulan bukan perikatan, yang menunjukkan bahawa kebanyakan syarikat penerbangan dalam kumpulan perikatan telah melakukan usaha yang hebat untuk mengurangkan pelepasan, dan potensi pengurangan pelepasan tidak sebesar syarikat penerbangan kumpulan bukan perikatan. Tesis ini mencadangkan satu siri pendekatan DEA yang lebih baik berdasarkan penyelidikan sedia ada, yang memperkaya dan mengembangkan kajian empirikal mengenai kecekapan penerbangan serta teori dan metodologi penilaian kecekapan DEA. Dengan menyepadukan struktur dinamik dan rangkaian, mengambil kira heterogeniti teknologi, dan mempertimbangkan strategi operasi yang berbeza, kajian ini menawarkan rangka kerja penilaian yang lebih komprehensif dan realistik untuk prestasi syarikat penerbangan. Oleh itu, tesis ini mempunyai nilai teori dan praktikal yang signifikan dalam membantu syarikat penerbangan meningkatkan prestasi operasi dan alam sekitar mereka. Selain itu, ia menyediakan asas objektif untuk membuat keputusan, membolehkan pengurus dan penggubal dasar merangka strategi sasaran yang memupuk industri penerbangan yang lebih cekap, berdaya saing dan mampan alam sekitar. Penemuan ini bukan sahaja menyumbang kepada kesusasteraan akademik tetapi juga menawarkan pandangan yang boleh diambil tindakan untuk menambah baik peruntukan sumber dan mengimbangi pertumbuhan ekonomi dengan tanggungjawab alam sekitar dalam sektor penerbangan.

EVALUATING OPERATIONAL PERFORMANCE, ENERGY AND CO_2 EFFICIENCY AND COST OF POLLUTION OF AIRLINES USING NETWORK DEA APPROACH

ABSTRACT

The airline industry can only achieve sustainable development if it ensures economic development and controls environmental pollution. However, the airline industry faces a huge challenge to its sustainability because the demand for transportation is strong, but profitability is low and is accompanied by a sharp increase in undesirable outputs. How airlines can make more efficient use of input resources, maximise desirable outputs, reduce undesirable outputs, and operate efficiently is an urgent issue for research. This thesis addresses this research problem using Data Envelopment Analysis (DEA), which is widely used for efficiency evaluation due to its ability to handle multiple inputs and outputs without the need for a priori assumptions on the functional form. Considering the technological heterogeneity of different airlines in terms of their operational structure (whether they participate in dynamic strategic alliances or not), this thesis first constructs a union dynamic network data envelopment analysis (DNDEA) model under a metafrontier framework to evaluate the dynamic operational performance of 24 global airlines from 2017 to 2019. It is found that the dynamic overall meta-efficiency of the alliance group was significantly higher than that of the nonalliance group. This suggests that joining strategic alliances can have a positive impact on an airline's operational performance. DNDEA can provide a comprehensive and dynamic picture of the operational efficiency of airlines over time, helping airlines and policymakers to better optimise resource allocation and achieve sustainable development. Next, a range-adjusted measurement network data envelopment analysis (RAM-NDEA) model was constructed under a metafrontier framework to evaluate unified, energy and CO_2 efficiency scores for 59 global airlines in 2019 under natural disposability, managerial disposability and the unification of the two disposability concepts. The empirical results show that the unified overall efficiency of the alliance group is greater than that of the nonalliance group under all three UE measures, and the energy and CO_2 efficiencies of the alliance group are greater than that of the nonalliance group under managerial disposability and the two disposability concepts, which suggests that joining the alliance is conducive to the enhancement of the airlines' unified performance and environmental performance. In addition, a positive interaction of natural and managerial disposability on unified efficiency was found for most airlines. This indicates the advantages of unified efficiency measures and the feasibility of achieving sustainable development by balancing operational and environmental performance improvements. Finally, this thesis constructs a non-radial directional distance function (NDDF) dual model and calculates the marginal abatement cost (MAC) of CO_2 for 59 global airlines in 2019 to understand the abatement potential of airlines. The results show that the average MAC of the alliance group is larger than that of the nonalliance group, which indicates that most of the airlines in the alliance group have already made great efforts to reduce emissions, and the emission reduction potential is not as large as that of the nonalliance group airlines. This thesis proposes a series of improved DEA approaches based on existing research, which enrich and expand the empirical studies on airline efficiency as well as the theory and methodology of DEA efficiency evaluation. By integrating dynamic and network structures, accounting for technological heterogeneity, and considering different operational strategies, this study offers a more comprehensive and realistic assessment

framework for airline performance. Therefore, this thesis holds significant theoretical and practical value in assisting airlines to enhance both their operational and environmental performance. Moreover, it provides an objective foundation for decision-making, enabling managers and policymakers to formulate targeted strategies that foster a more efficient, competitive, and environmentally sustainable airline industry. The findings not only contribute to academic literature but also offer actionable insights for improving resource allocation and balancing economic growth with environmental responsibility in the aviation sector.

CHAPTER 1

INTRODUCTION

1.1 Overview

Economic globalisation and regional economic integration are current trends in the global economy that are rapidly transforming and reshaping the ways in which resources are allocated and goods flow on a global scale. The international division of labour gradually tends to be interdependent and complementary, and the distribution of raw materials, core technologies, and manufactured goods is no longer confined to developing or developed countries; instead, goods and services circulate globally in a more integrated manner. Moreover, the intensification of trade dependence among countries also signals a more frequent flow of people and goods across countries and regions. Against this backdrop, the development of the global logistics industry has undergone profound changes and gained increasing attention. As an integral component of the global logistics and transportation system, the air transportation industry is becoming increasingly important, playing an irreplaceable role in international and domestic medium- and long-distance high-speed passenger and cargo transportation. Safe, reliable, and cost-effective air transportation is integral to the broader strategy for achieving the United Nations (UN) Sustainable Development Goals (SDGs) by 2030 (ATAG, 2020).

The airline industry, as a significant component of measuring the Logistics Performance Index (LPI), plays an irreplaceable and important role in facilitating the globalisation of trade, creating economic value, providing convenient transportation, and promoting technological progress. Despite the economic challenges posed by the COVID-19 pandemic, the demand for air travel remains strong and is expected to double from 4 billion passengers in 2019 to just over 8 billion by 2040, with an average annual growth rate of 3.4% (IATA, 2023). The huge demand for air transportation has also led to significant energy consumption, with jet fuel costs consistently representing the largest portion of airlines' total expenses. In 2018, fuel expenses accounted for 24% of airlines' total operating costs (IATA, 2019). The burning of fuel by aircraft during flight inevitably produces greenhouse gases, an undesirable output that is considered responsible for global warming.

Global warming is threatening the survival of people worldwide, and the frequency of extreme weather has caused widespread international concern (Ji et al., 2021; Raghutla & Chittedi, 2020). This phenomenon represents one of the most pressing global concerns of our time. Scientists have attributed the main cause of climate change to greenhouse gas emissions (Boussemart et al., 2017; Solomon et al., 2007), and CO_2 emissions account for more than three-quarters of greenhouse gas emissions (Meng, 2019). CO_2 abatement is a global issue that is relevant to the sustainable development of humans and society. According to the UN Intergovernmental Panel on Climate Change (IPCC), global CO_2 emissions would have to be reduced by at least 20% by 2030 compared to 2010 emissions to meet the Paris Agreement's goal of limiting the increase in global average temperature to 2° C compared to pre-industrial levels, with efforts to limit the increase to 1.5°C (Rogelj et al., 2018). However, the carbon emissions data show that there is still a long way to go to reach the targets of the Paris Agreement. Thus, policymakers and industry stakeholders should actively take measures to curb CO_2 emissions.

In 2019, global direct greenhouse gas (GHG) emissions from the transport sector were 8.7 $GtCO_2$-eq, accounted for 23% of energy-related CO_2 emissions, with road vehicles, aviation, shipping, and rail emissions accounting for 70%, 12%, 11%, and 1%, respectively, of which aviation and shipping emissions are growing rapidly (IPCC, 2023). Aviation is the second largest transport mode in terms of CO_2 emissions, and aircraft, which typically fly in the stratosphere, are high-altitude emitters whose carbon emissions per kilometre have twice the environmental impact of the surface (Brueckner & Abreu, 2017). According to the International Energy Agency (IEA, 2022), the aviation industry contributed to over 2% of global energy-related CO_2 emissions in 2021, outpacing the growth of roads, rail, and shipping in recent decades. Therefore, carbon emissions from aviation have a pivotal role in global climate change. In recent years, there has been a proliferation of issues related to the environment in the aviation industry, and policymakers and decision-makers have become increasingly concerned about carbon emissions from aviation and have developed various aviation policies in support of the Sustainable Development Goals (SDGs). Global initiatives, including the European Union Emissions Trading System (EU-ETS) and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), have been introduced to reduce carbon emissions (Mai, 2021). In the face of strong aviation demand and increasing pollution, whether and how airlines can achieve sustainable practices that balance economic benefits and environmental protection are questions that are worth investigating.

1.2 Research Background

1.2.1 The Importance of the Airline Industry in Achieving the SDGs Strategy

Air transportation is at the heart of global economic growth, creating jobs, facilitating trade, and promoting tourism. Trade and travel play significant roles in modern life and commerce, and air transport contributes to sustainable development in countries worldwide. The airline industry has contributed to promoting social development, generating economic benefits, and promoting environmental responsibility (IATA, 2020).

In terms of social development, financial data for the airline industry published by the International Air Transport Association (IATA, 2020) show that in 2019, 58% of international tourists travelled by air, and the world's 1,478 commercial airlines operated 46.8 scheduled million commercial flights, transporting 4.5 billion passengers. On an average day in 2019, approximately 128,000 flights were operated, carrying 12.5 million passengers and goods valued at USD18 billion. Global airline transportation provides a vital link between countries worldwide, including small islands and remote regions. Furthermore, it also plays an irreplaceable role in advancing social development by being relevant to 15 of the 17 SDGs.

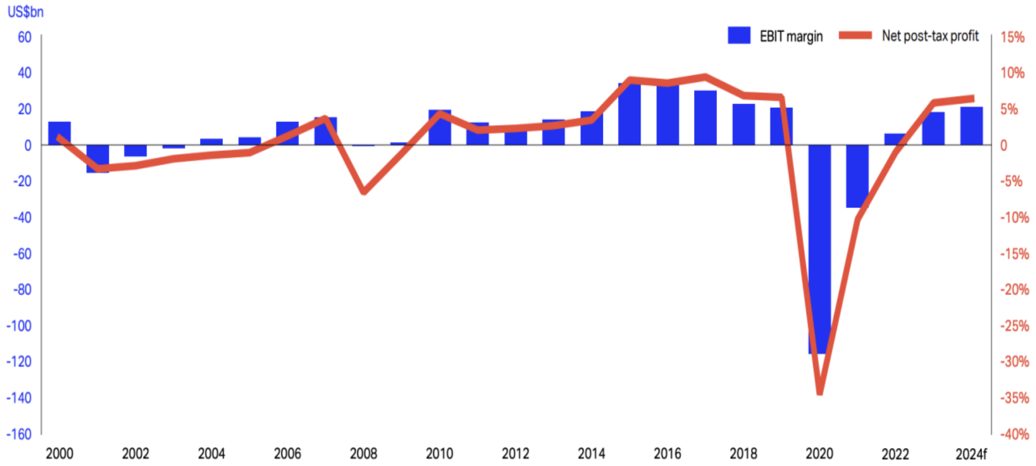
In terms of economic benefits, aviation contributed US D350 trillion to global GDP in 2018, accounting for 4.1% of world economic activity and 35% of global trade by value of transportation. Aviation contributed 87.7 million jobs globally. This encompassed 11.3 million direct aviation-related jobs, 18.1 million aviation supply chain jobs, 13.5 million jobs from induced benefits resulting from aviation and employee spending, and 44.8 million jobs supported within the tourism sector.

In terms of environmental responsibility, in 2008, the airline industry set the world’s first global aviation CO_2 reduction targets: 1) improve aircraft fuel efficiency by an average of 1.5% per annum between 2009 and 2020; 2) stabilise net CO_2 emissions from 2020 through carbon-neutral growth to be achieved through CORSIA of the International Civil Aviation Organization (ICAO); and 3) reduce net aviation CO_2 emissions to half of 2005 levels by 2050 through sustainable aviation fuels (SAF) and new technologies. The airline industry reduced CO_2 emissions per passenger kilometre by 54.3% and 11 billion tons, respectively, from 1990 to 2019 through new technologies, better operations, and infrastructure improvements. Airlines spend an average of USD15 billion a year on research to improve the technical efficiency of their aircraft and have been actively taking responsibility for and taking action to reduce energy conservation emissions and protect the environment. Therefore, the airline industry plays an essential facilitating role in achieving the SDGs (IATA, 2020).

1.2.2 Resilience of the Airline Industry and the Overall Positive Development Trend

The airline industry promotes world interconnectivity, trade, and socioeconomic development and is affected by international politics, economic volatility, and environmental constraints. The airline industry faced substantial setbacks due to significant events such as the 9/11 terrorist attacks, the 2007-2008 global financial crisis, and the 2020 COVID-19 pandemic. Among these, the COVID-19 pandemic due to border restrictions stands out as having the most profound impact on air travel and the airline industry since World War II. According to the IATA: COVID-19 Analysis Fact Sheet (IATA, 2021), the airline industry suffered cumulative losses of USD20.1 billion from 2020 to 2022. The global airline industry has continued to rebound since the pandemic after experiencing 65.9% and 58.4% decreases in passenger demand (measured in revenue passenger kilometres (RPK)) in 2020 versus 2019 and 2021 versus 2020, respectively, and passenger demand has risen 64.4% in 2022 versus 2021 and 36.9% in 2023 versus 2022. At the same time, cargo demand (measured in freight tonne-kilometres (FTK)) has also rebounded. This pushed the total global air demand for passengers and cargo in 2023 to only slightly below pre-pandemic levels in 2019

Figure 1.1 shows global airline profitability as analysed by IATA in the Global Outlook for Air Transport: A local sweet spot in December 2023 (IATA, 2023). As shown in Figure 1.1, after a period of rebound from the triple whammy (the 9/11 terrorist attacks, the 2007-2008 global financial crisis, and the 2020 COVID-19 pandemic), in which airlines' earnings before interest and taxes (EBIT) margin and net post-tax profit were significantly reduced, the industry rebounded quickly from almost a complete standstill and overall growth in the long term continued to increase. Compared to the historic nearly USD 140 billion loss in 2020, the airline industry returned to profitability in 2023. This impressive turnaround underscores the industry's resilience, adaptability, and overall positive trajectory.

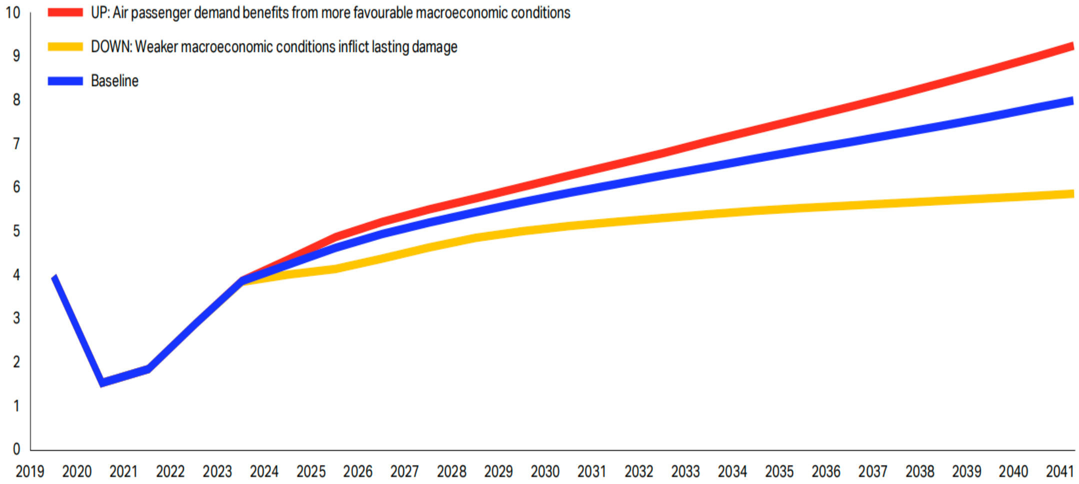


Source: IATA Sustainability and Economics, The Airline Analyst (2023)

Figure 1.1 Global Profitability, Billion

As shown in Figure 1.2, IATA forecasted global air passenger traffic from 2023 to 2040 in the up, down, and baseline scenarios (IATA, 2023). In the upside scenario, air passenger demand might experience a boost from improved macroeconomic conditions, including stabilised supply chains and reduced inflation rates, potentially leading to an earlier easing of current monetary policy measures. Conversely, in the downside scenario, risks loom large due to the strength of the business cycle and uncertainties surrounding the extent and impact of conflicts in regions like Ukraine and the Middle East. At the baseline level, global air passenger traffic will increase by 4.2%

per year, a slower growth rate compared to the pre-pandemic period, but overall air passenger traffic will more than double from 2019 levels to 8 billion passengers by 2040. Air transportation advances connectivity between countries and cities and is an important and necessary contributor to global economic development, and continued growth in air passenger traffic will contribute more broadly to social development and economic growth.

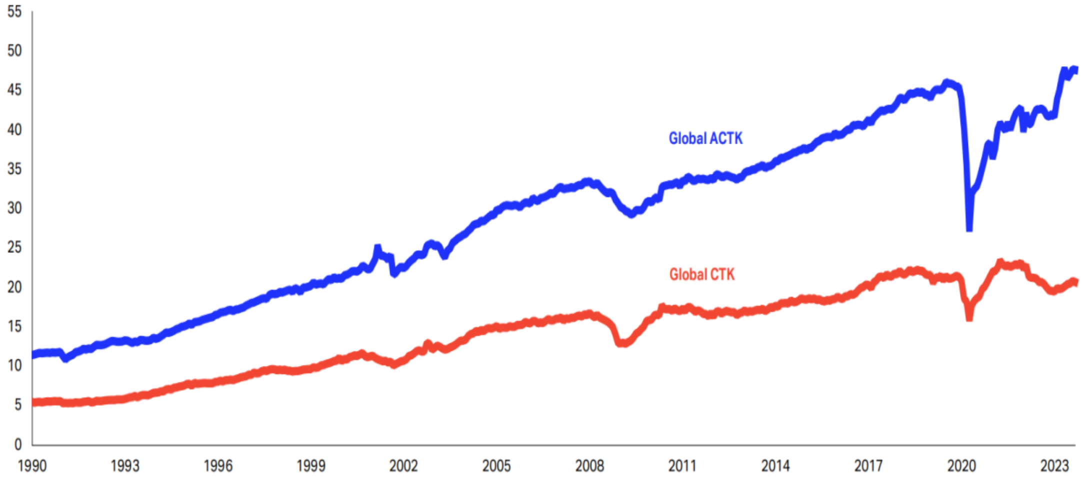


Source: IATA Sustainability and Economics, Tourism Economics (2023)

Figure 1.2 Global Air Passenger Journeys, Billion

On the air cargo side, industry-wide cargo volumes have also managed to rebound after a downturn. Figure 1.3 shows the seasonally adjusted global available cargo tonne kilometres (ACTK) and global cargo tonne kilometres (CTK) demand from 1990 to 2023 (IATA, 2023). Cargo performance remained strong during the pandemic, especially in 2021. However, in 2022, the cargo market experienced significant downward pressure due to the converging effects of global trade and economic growth, the war in Ukraine, high inflation in major markets, and rising global oil prices. By the beginning of 2023, cargo capacity continued to grow and, in April 2023, exceeded pre-pandemic levels. There has been some volatility in global air ACTK and CTK volumes over the long term due to a variety of factors, but the overall dynamic remains positive.

Even though the airline industry's 2023 passenger (Figure 1.2) and cargo (Figure 1.3) demand is already approaching and exceeding pre-pandemic levels, respectively, the industry had a net profit margin of only 2.6% in 2023, which equates to USD5.44 per passenger, and 2024 profitability is expected to be approximately the same as that in 2023 (IATA, 2023). Intense intra-industry competition and rising operating costs, such as fuel prices and labour costs, have made the profitability of the aviation industry a great challenge, and how to improve operational efficiency and increase profits against the backdrop of increasing demand for capacity is a dilemma that plagues airline managers and decision-makers.



Source: IATA Sustainability and Economics, IATA Monthly Statistics (2023)

Figure 1.3 Seasonally adjusted global ACTK and global CTK, Billion

1.2.3 The Operational Context for Airlines: Dynamic Competition and Strategic Alliances

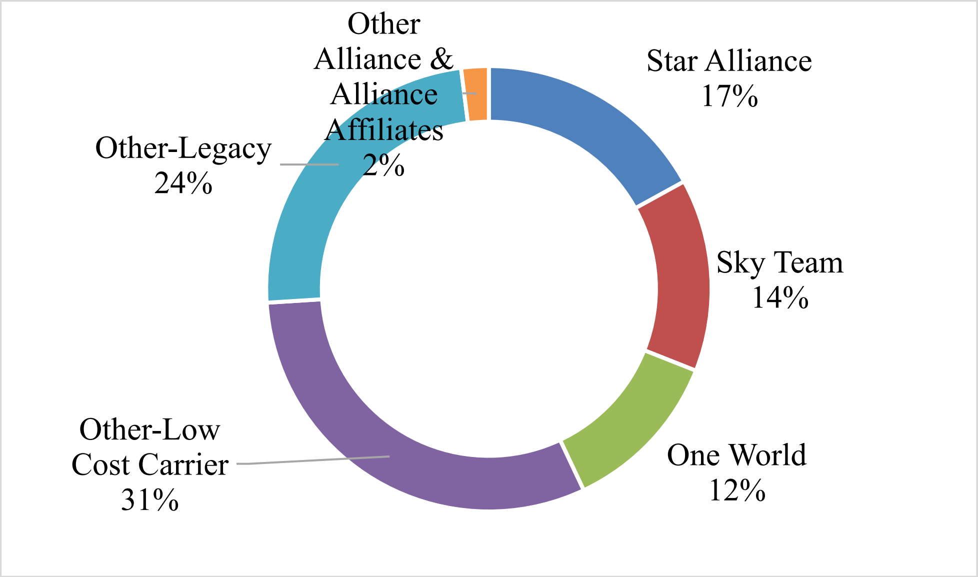
Over the past half-century, in addition to the international situation, the economic situation, the trade environment, and other factors affecting the development of the airline industry, the business environment of the airline industry itself has also changed dramatically. The liberalisation and deregulation of the airline industry in Europe and the United States and the "Open Skies" policy in Asia and Latin America have led to the globalisation of competition in the aviation market, which has stimulated the development of air transport and intensified competition in the global airline industry, resulting in considerable cost challenges and a complex business environment for airlines. The combination of rising oil prices, infrastructure inputs, labour costs, and interest rates has put additional pressure on airlines and poses significant challenges to the industry's operations and profitability. According to the report from IATA, the airline industry does have a meagre net profit margin of 2.6% in 2023, which equates to a modest USD5.44 on a per-passenger basis, while an oil company and large tech companies have net profit margins of approximately 11% and 22%, respectively. IATA's projected profitability for 2024 is also not optimistic, with a projected net profit margin of 2.7%, which equates to a net profit of USD5.45 per passenger—less than a cup of cold brew coffee in Geneva (IATA, 2023). This suggests that there is room for improvement in terms of cost control and increased profitability; hence, there is an urgent need for airlines to reduce costs and improve efficiency. Most studies define it as the relationship between the inputs and outputs of an airline's operations or its allocation of resources. From the input perspective, airline efficiency measures the ability to achieve a certain output with minimum inputs; from the output perspective, efficiency measures the ability to maximise output products or services using a certain number of resources (e.g., employees, fuel). From a simple input-output perspective, airline efficiency can be expressed as the ratio of the quantity of outputs to the quantity of inputs. Evaluating airline operations performance can not only improve the efficiency of airline operations and management but also, more importantly, reduce carbon emissions and promote the sustainable development of airlines (Liu & Jiang, 2023).

To capture market share in the face of intense commercial competition, many low-cost carriers (LCCs) entered the market in the 1970s, quickly gaining their foothold by offering point-to-point services at low fares. At the same time, traditional full-service carriers (FSCs) lost their market share due to the high cost of services. In this context, FSCs formed alliances to compete with LCCs. There are many definitions of airline alliances, among which Mohr and Spekman (1994) proposed a more accurate definition of an airline alliance, which is "a purposeful organisation of airlines that share a common goal and enjoy a high degree of autonomy in their management."

Improving operational efficiency is one incentive for an airline to join an alliance (Kottas & Madas, 2018; Min & Joo, 2016). Three of the world's largest passenger airline alliances are the Star Alliance, SkyTeam, and OneWorld. According to the analysis of the Official Airline Guide (OAG, 2023), as of May 2023, 60 airlines worldwide have joined one of these three major airline alliances, with the Star Alliance having the most members, with a total of 26 airlines. Since the three major airline alliances comprise the world's major airlines, their share of capacity has exceeded 40% of global air passenger traffic, as shown in Table 1.1. OAG also analysed the global capacity share in the 12 months ending in May 2023, as shown in Figure 1.4. The three major alliances accounted for 43% of the route capacity, LCCs that are not part of an alliance operated 31% of the route capacity, other alliances and alliance affiliates accounted for 2%, and other legacy alliances accounted for 24%.

Table 1.1 Status of the Three Major Airline Alliances

Alliance	Members	Destinations	Countries	Daily Flights	Capacity Share
Star Alliance	26	1289	192	15324	17%
Sky Team	19	1058	169	11983	14%
One World	15	998	175	11156	12%
Total	60				43%



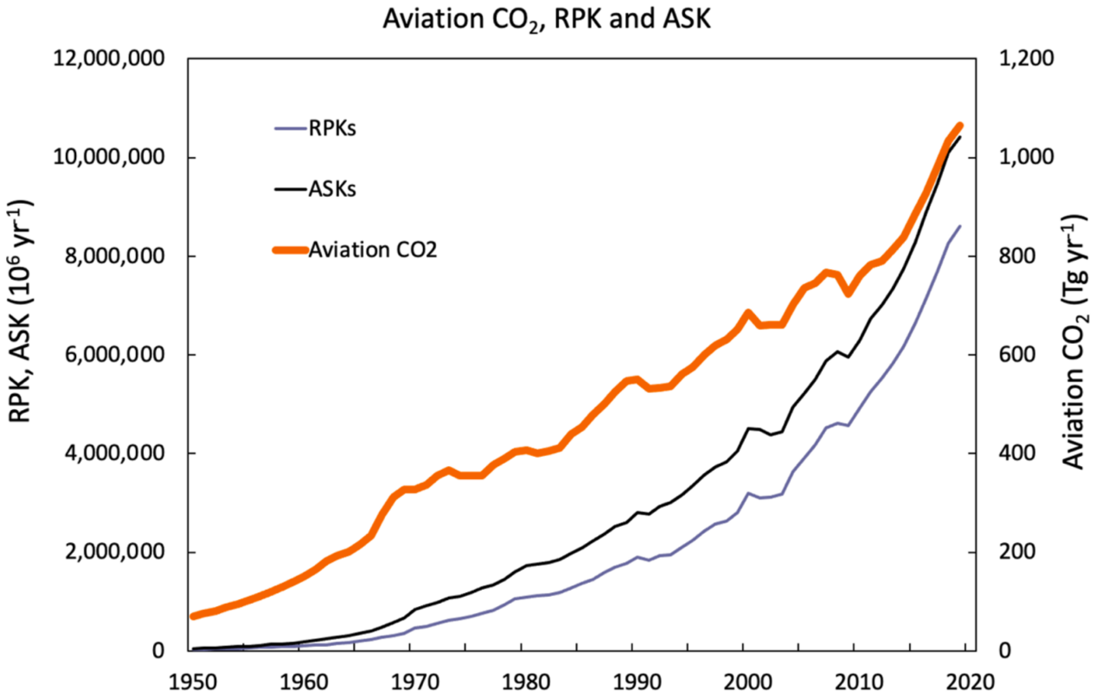
Source: Aviation Infographics of the Month from OAG

Figure 1.4 Global Capacity Share (12 Months to May 2023)

Strategic alliances provide a new paradigm for global companies to re-examine their competitors (Fadol, 2010). As global competition intensifies, it is often difficult for individual airlines to cope with continued dynamic competition and innovation, and they may not be able to achieve their strategic objectives in the global marketplace by solely relying on their own resources. The world's major airlines have sought strategic partners to cooperate with their competitors to share resources and risks, thereby enhancing their overall competitive advantage (Oum et al., 2004). The forms of cooperation in airline alliances mainly include joint marketing, joint operation, joint purchase investment, and equity participation (Bronder & Pritzl, 1992). A strategic alliance is actually a strategic goal of several enterprises to expand the market, complement each other's advantages, and share resources and risks while maintaining each enterprise's independence (Prashant & Harbir, 2009). Companies form a loose cooperative and competitive organisation with other enterprises through agreements to improve airline transportation efficiency and realise mutual economic benefits. Depending on whether they choose to join a strategic alliance or not, airlines are more likely to be different in terms of operational management (alliance airlines usually enhance their operational management through resource sharing, code-sharing and collaborative arrangements, while nonalliance airlines are more likely to operate alone), market competitiveness (alliance airlines gain market share through cooperation, while nonalliance airlines may be more focussed on specific market segments or regions and adopt flexible competitive strategies to respond to competitive pressures), cost structure (alliance airlines may reduce operating costs through collective purchasing, sharing of ground service resources, joint marketing, etc., while nonalliance airlines may find it more difficult to achieve economies of scale), and service quality (alliance airlines usually provide more consistent service standards to enhance customer loyalty, while nonalliance airlines may rely on price competition or differentiated service strategies to attract customers), etc. It can be seen that there is technological heterogeneity between alliance and nonalliance airlines (Yu et al., 2024), and both models have their own strengths and challenges, creating distinctive characteristics and competitive dynamics of airlines in the global aviation industry.

1.2.4 Environmental Challenges for Airlines

Airlines, as a key enabler of globalisation, face a number of significant environmental challenges, particularly as global concerns about climate change and sustainable development intensify. The first is the issue of greenhouse gas emissions. With the relaxation of COVID-19 border restrictions in various parts of the world and the subsequent global economic recovery, the anticipated growth of the airline industry will generate a significant increase in the sector's share of global carbon emissions. On March 20, 2023, the UN IPCC released the IPCC AR6 Synthesis Report, shown in Figure 1.5, which presented historical global aviation CO_2 emissions from 1950 to 2020 and as capacity and transportation (measured in available seat kilometres (ASK) and revenue passenger kilometres (RPK), respectively) continue to increase, carbon emissions also dramatically increase (IPCC, 2023). According to the ICAO (2019), the annual value of aviation will be two to four times that of 2015 by 2050 in absolute terms. Given a laissez-faire approach, aviation emissions are predicted to contribute 25% of the global carbon budget by 2050 (Núñez Alfaro & Chankov, 2022).



Source: Report of the Sixth Assessment Report (IPCC, 2023)

Figure 1.5 Historical Global Emissions of CO_2 from Aviation

Second is the issue of fuel efficiency and dependence on fossil fuels. Fossil fuels are both finite and environmentally harmful, but the aviation industry currently relies heavily on fossil fuels. Aviation is widely recognised as a "difficult industry to decarbonise" (Gota et al., 2019), as it relies heavily on liquid fossil fuels and has long infrastructure "lock-in" times, resulting in slow fleet turnaround times. The IPCC (2023) stated that CO_2 from the combustion of the fossil fuel kerosene is the primary GHG in aviation-related emissions. The substantial demand for air transportation is poised to escalate energy consumption, exacerbating the disparity between energy supply and demand, especially with constrained refinery capacity. The Russia-Ukraine war in February 2022, coupled with a sustained recovery in aviation demand over the same period, caused the price of crude oil to rise for the first time in a decade, exceeding USD120 per barrel. Although oil prices have fallen back from their peak, they remain high, increasing airlines' operating costs and posing significant challenges to the industry's profitability (IATA, 2023). In 2023, fuel costs of the global aviation industry were estimated to reach USD 271 billion, or approximately 32% of operating expenses. There is an urgent need for airlines to improve their energy efficiency to cope with external challenges such as high oil prices and stricter environmental regulations.

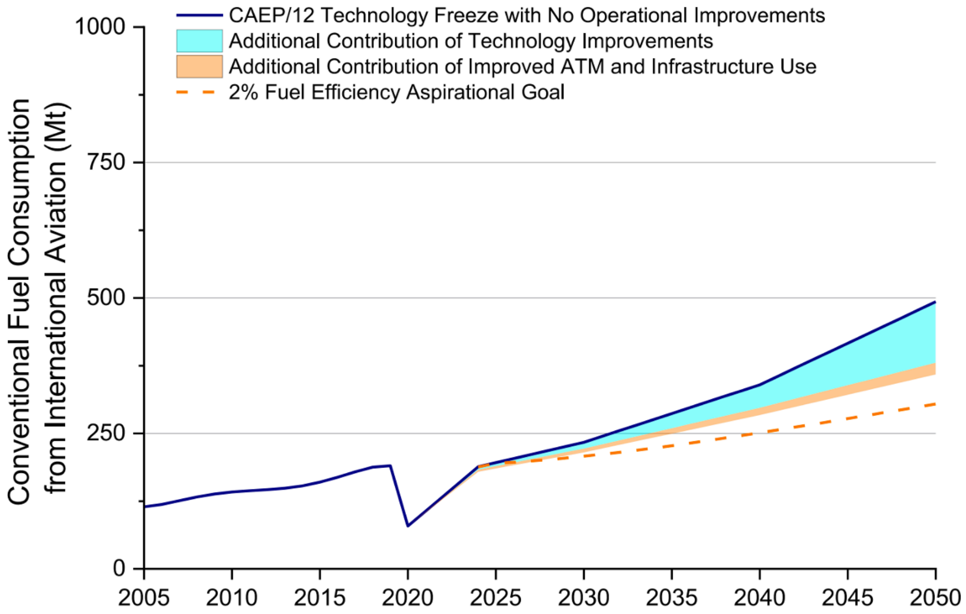
Other environmental challenges include noise pollution, which can negatively impact communities due to the noise generated by aircraft landing and taking off. Airlines also generate waste such as single-use plastic packaging and food waste. This study focuses on greenhouse gas emissions and energy fuels from airlines.

1.2.5 Carbon Emission Abatement Measures

To advance the aviation industry's goal of decarbonisation, help it mitigate the huge challenge of its environmental impact and maintain the long-term sustainable development of the industry, controlling carbon emissions from aviation is an urgent task for mitigating environmental pollution. Statistics from the International Council on Clean Transportation (ICCT) indicated that global aviation activities for both passengers and cargo emitted around 920 million tons of CO_2 in 2019, marking a 30% rise from 2013 (Graver et al., 2020). Given the need and urgency for the airline industry to mitigate its carbon emissions, in 2009, the IATA established a target to achieve carbon-neutral growth beginning in 2020 and mitigate emissions by 50% from 2005 levels by 2050 (IATA, 2009). As the United Nations specialised agency for global civil aviation, ICAO plays an important role in promoting environmental protection and sustainable development in the aviation industry.

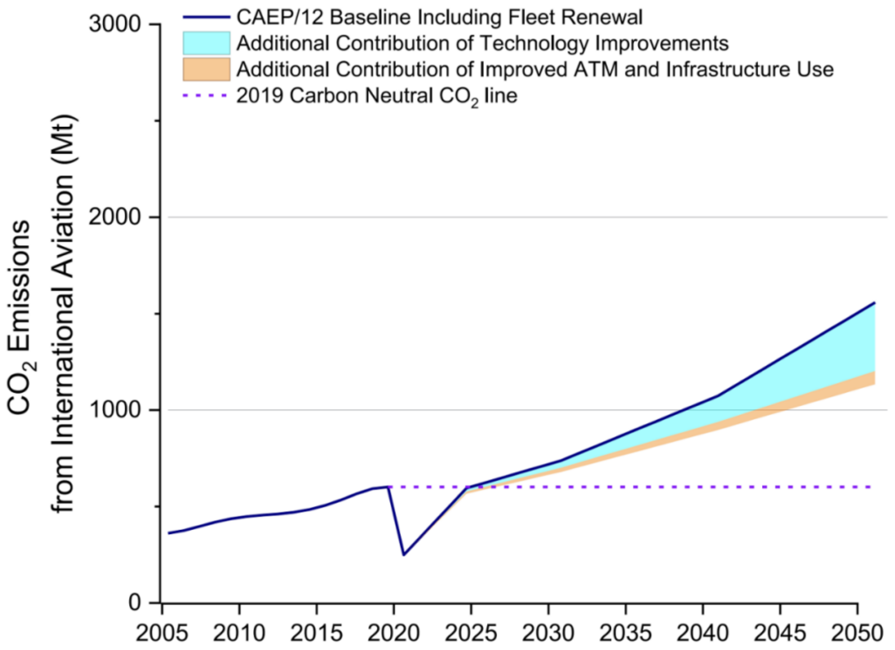
ICAO (2022) predicted full-flight fuel burn and CO_2 emissions under different scenarios in Environmental Trends in Aviation to 2050. Figures 1.6 and 1.7 depict the outcomes concerning full-flight (from departure gate to arrival gate) fuel burn and CO_2 emissions, respectively, for international aviation spanning from 2005 to 2050. The analysis encompasses the influence of aircraft technology, enhanced Air Traffic Management (ATM), and infrastructure utilisation (i.e., operational improvements) on fuel consumption and CO_2 emissions. In Figure 1.6, the dashed line represents the expected fuel burn if ICAO's 2% annual fuel efficiency aspirational goal was attained. Figure 1.7 illustrates that CO_2 emissions are solely derived from jet fuel combustion, assuming that 1 kg of burnt jet fuel generates 3.16 kilograms of CO_2.

Figures 1.6 and 1.7 illustrate that additional contributions of operational and technology improvements can reduce energy consumption and CO_2 emissions. Energy efficiency can decrease fuel consumption and thus reduce CO_2 emissions. Therefore, effective carbon emission abatement measures are, first, operational improvement measures, mainly in terms of airline operational efficiency (including aircraft weight reduction, route optimisation, etc.) and security capacity; and second, technology improvements, such as more fuel-efficient aircraft, better fuel efficiency, and the use of sustainable aviation fuels (SAFs). In addition, ICAO believes that market-based regulatory measures are also effective ways to reduce carbon emissions. CORSIA, the world's first sectoral carbon-pricing initiative based on market-based mechanisms, was adopted by the 39th General Assembly on 7 October 2016. It has made the aviation industry the world's first to implement a global measure through an agreement by governments. CORSIA's goal is that an increase in international flights after 2020 should not result in additional CO_2 emissions, i.e. to achieve carbon-neutral growth in international aviation from 2020 onwards. This target is achieved in two ways: through carbon reduction measures (operational improvements and technological improvements) and through carbon offsets, i.e. airlines offsetting the additional emissions they generate by purchasing carbon credits.



Source: Environmental Trends in Aviation to 2050, ICAO (2022)

Figure 1.6 Fuel Consumption from International Aviation, 2005 to 2050



Source: Environmental Trends in Aviation to 2050, ICAO (2022)

Figure 1.7 CO_2 Emissions from International Aviation, 2005 to 2050

In addition to CORSIA, the EU included aviation in its carbon Emissions Trading System (ETS) market in 2012, requiring airlines to declare the carbon emissions from their flight activities and purchase the corresponding carbon allowances, and although the system currently only applies to intra-EU flights, it has prompted more countries to join the global efforts to reduce emissions. Carbon emission reduction measures based on market mechanisms, which are considered an effective method for reducing carbon emissions, can influence the market through price leverage (Chiu et al., 2015) and are more capable of motivating market players to save energy and reduce emissions (Chen & Groenewold, 2015). The marginal abatement cost (MAC) of carbon refers to the additional cost required for each unit of carbon emission reduction at a given emission level. MAC, a form of corporate internal carbon pricing (ICP), is a strategy for crystallising the risk of carbon emissions in monetary terms and is normally employed directly in investment decisions as an additional indicator for quantifying climate-related risks in business assessments without actual payments being involved.

Due to its ease of implementation and favourable long-term effects, the MAC has emerged as the most commonly utilised ICP tool among companies (Ahluwalia, 2017; Bartlett et al., 2017). In the carbon emissions trading market, the price of carbon allowances is affected by the MAC. If airlines find it more cost-effective to buy carbon allowances in the market than to take more expensive abatement measures, the demand for carbon allowances will rise, leading to an increase in the price of carbon in the market. The MAC is an important indicator of the price of carbon in the market.

1.2.6 Main Approaches for Airline Performance Evaluation

The airline industry faces a huge challenge to its sustainability because the demand for transportation is strong, but profitability is low and is accompanied by a sharp increase in undesirable outputs. The more efficient use of input resources by airlines and the maximisation of desirable outputs while reducing undesirable outputs, i.e., airline performance evaluation, are major concerns for airline managers and decision-makers. To survive and thrive in a rapidly changing and extremely competitive business environment, improving airline efficiency is not only a crucial concern for both policymakers and managers but also has attracted the research interest of numerous scholars. Efficiency is the comparative position of the analysed unit compared to the best-practice frontier, with the latter being defined by the group of airlines being studied. Measures of efficiency can be divided into two main categories: parametric methods and nonparametric methods. Among them, parametric methods mainly include parametric linear programming (PLP), stochastic frontier analysis (SFA), and econometric methods; nonparametric methods mainly include data envelopment analysis (DEA).

Many scholars have used quantitative methods to measure airline performance and efficiency, such as total factor productivity (TFP) (Barbot et al., 2008; Bauer, 1990;

Caves et al., 1983; Oum & Yu, 1995), DEA (Alam, 1998; Bhadra, 2009; Capobianco & Fernandes, 2004; Cui & Li, 2015; Schefczyk, 1993; Wang et al., 2019), SFA (Good, 1993; Good et al., 1995; Tsionas et al., 2017), etc. Table 1.2 compares the advantages and disadvantages of parametric and non-parametric approaches; both types of approaches have unique advantages and unavoidable drawbacks. Yakath Ali et al. (2021) reviewed the literature on airline productivity and efficiency evaluation over the last 40 years and found that the DEA was the most used methodology for measuring airline efficiency over the period 1979-2020 due to its fewer data requirements and versatility, followed by SFA. However, the literature on SFA is much less extensive than that on DEA. Therefore, this thesis considers the use of the DEA approach to evaluate the efficiency of airlines.

Table 1.2 Parametric versus Non-parametric Approaches

Approach	Advantages	Disadvantages
Parametric methods	(1) With economic theory and connotations; (2) Multi-order derivable; (3) Provide parameter estimates	Many assumptions: functional form assumptions, distributional assumptions, etc.
Nonparametric methods	(1) No assumptions are required; (2) Simple to compute; (3) Wide applicability	(1) Lacks economic theory; (2) Unable to provide parameter estimates

The data envelopment analysis (DEA) model originated from production efficiency and was initially proposed by Charnes et al. (1978) which can measure the relative efficiency of decision-making units (DMUs) with multiple inputs and multiple outputs and does not need prior assumptions about the form of the production or utility function, which is not possible with the parametric method. Therefore, the DEA approach is an important nonparametric method that has been widely adopted to evaluate the performance of the airline industry (Barros & Wanke, 2015; Chen et al., 2017; Cui & Li, 2017; Li & Cui, 2017a; Wanke et al., 2015).

Scholars have explored various aspects of airline performance using the DEA approach, including operational efficiency (Kottas & Madas, 2018; Tavassoli et al., 2016; Yu & See, 2022), environmental efficiency (Chang et al., 2014; Cui & Jin, 2020; Li & Cui, 2017a), energy efficiency (Cui et al., 2018; Fukuyama et al., 2020; Teng et al., 2022), carbon emission efficiency (Geng et al., 2013; Liu & Jiang, 2023), and productivity (Choi, 2017; Wang et al., 2022; Yu & Chen, 2023). Operational efficiency refers to the ability to maximise returns from minimal inputs through management tools and strategies and is an important measure of an airline's business performance. The operational efficiency of airlines has received the most attention from scholars, and many related studies have been conducted. In recent years, the environmental problems caused by the rapid development of the airline industry have also attracted the attention of scholars, and the number of studies on environmental efficiency, energy efficiency, and carbon emission efficiency has risen accordingly.

Earlier studies usually used traditional DEA models such as those of Banker and Johnston (1994), Capobianco and Fernandes (2004), and Hong and Zhang (2010) to evaluate airline efficiency. In the process of airline operation, through initial inputs such as fuel cost, number of aircraft, and number of employees, intermediate outputs such as available tonne kilometres (ATK) and ASK are generated, and through the sale of intermediate outputs, final outputs such as revenue freight kilometres (RFK) and RPK are obtained. Notably, these intermediate outputs are not storable, and the unsold freight and passenger capacity will not create value once the aircraft takes off (Chiou et al., 2010). Therefore, maximising the production and utilisation of intermediate outputs is an essential element of airline performance evaluation that cannot be ignored. The traditional DEA model only focuses on the initial inputs and final outputs of DMUs, ignoring the relationships within the "black box", so the model can only evaluate the efficiency of the airline as a whole but not the intermediate stages of the airline (Liu et al., 2023). For more insight into the inefficient processes/stages within the system, Färe (1991) proposed the network DEA (NDEA) model for the first time by considering a multistage network structure. This NDEA, which adds additional structures to the traditional DEA model, is better suited for applications where the DMU consists of multiple substructures (Färe & Grosskopf, 2000a). Airline operations consist of multiple processes/stages that may generate intermediate outputs that can serve as inputs to the next process/stage, resulting in a network structure. Evaluating the efficiency of each process/stage based on its network structure allows for a more accurate assessment of the airline's operational performance. It identifies sources of inefficiencies so that performance improvement measures can be proposed more effectively.

In addition to the NDEA, dynamic DEA and metafrontier DEA have also been popular research topics in the field of airlines in recent years. Dynamic DEA evaluates the dynamic performance of DMUs over time. The airline operation process has inter-period dynamics and carry-over products, which affect the production operation in the subsequent period and connect the dynamic process between two consecutive periods. Metafrontier DEA considers the technological heterogeneity of airlines. Indeed, DMUs may be in different groups due to their different environmental characteristics, and comparing their performance needs to account for their technological heterogeneity (Kerstens et al., 2019). For example, airlines participating in alliances and airlines not participating in alliances will operate under different environmental characteristics and may lead to the existence of technological heterogeneity. Thus, the performance of these airlines is suitable for exploration in groups under a metafrontier framework to identify their technology gap. Battese et al. (2004) argued that the operational efficiency of DMUs may be overestimated or underestimated if their heterogeneous production structure is not considered. This study adopts the most widely used DEA model for airline performance evaluation and develops novel DEA models based on NDEA, dynamic DEA, and metafrontier DEA for assessing the performance of airlines and exploring the current status of sustainable development in the industry.

1.3 Problem Statement

The airline industry contributes to realising the global SDGs and has an important role in social development, economic benefits, and environmental responsibility. At the same time, with the development of global economic connectivity and the liberalisation of the aviation market, economic exchanges, cultural communications, and trade flows among countries have become increasingly frequent, contributing to the airline industry's rapid development. However, the rapid development of the airline industry has also been accompanied by several problems.

One important issue is that the rapid development of the airline industry has been accompanied by several environmental problems, the most prominent of which is the fact that air transportation has become a major source of carbon emissions. Air transportation is a significant contributor to global carbon emissions, and managing these emissions should be framed as an integral part of operational efficiency. A small number of studies have used dynamic NDEA models to evaluate the operational efficiency of airlines. However, only some studies have considered CO_2 to be an undesirable output variable, and airline efficiency evaluations that do not consider carbon emissions can lead to inaccurate or even incorrect results (Yu & See, 2022). Therefore, the existence of undesirable output of CO_2 must be considered when assessing the performance of airlines.

Another important issue is that the globalisation of the economy and environmental uncertainties has led to intense competition among airline companies and very meagre profit margins in the industry. Increasing input costs, such as fuel prices and labour, pose a significant challenge to airline profitability, and airlines must continue to adjust their operational strategies to improve operational efficiency. Currently, there is a research gap in integrating operational and environmental performance into a unified NDEA framework to simultaneously examine the sustainability of airlines in terms of both economic benefits and socioenvironmental aspects.

In addition, alliance and nonalliance airlines operate under different technological conditions. The alliance group and nonalliance group have different heterogeneous production structures, and therefore, each group has a different group frontier surface, so the efficiency of the two groups of airlines can be evaluated in a metafrontier framework. As a result, there may exist a technology gap in the operational and environmental performance between alliance and nonalliance airlines. Therefore, it is necessary to construct a DEA model under the metafrontier framework to evaluate the unified (operational and environmental) performance of alliance and nonalliance airlines, which can provide a basis for airlines under different business strategies to formulate strategies and measures to enhance economic efficiency and sustainable development.

In addition to operational improvement and technological innovation, market mechanisms, such as carbon emissions trading, can motivate airlines to save energy and reduce emissions. The MAC, as the most frequently used ICP tool among enterprises (Ahluwalia, 2017; Bartlett et al., 2017), reflects the opportunity cost of abatement and can measure the abatement potential of airlines (Zhou et al., 2014), providing a basis for airlines to formulate in-company abatement measures (Zhang et al., 2014), as well as a reference for setting prices in the carbon emissions trading market (Hueting, 1992). The MAC affects the role of the carbon emission market mechanism in the airline industry, and it is necessary to study how to measure the MAC reasonably.

1.4 Research Questions

Based on the above discussion, the following specific research questions are formulated:

(1) RQ1: In the presence of heterogeneity, what is the technology gap between alliance and nonalliance airlines in terms of operational performance? In the face of fierce competition, how can alliance and nonalliance airlines make more effective use of resource inputs to maximise output and thus improve operational efficiency?

(2) RQ2: Is it possible to evaluate the operational performance and environmental performance of airlines, as well as their energy and CO_2 efficiency, in a unified efficiency model and study the sustainable development status of alliance and nonalliance airlines in terms of economic benefits and social environment to promote economic, green, low-carbon, and sustainable development?

(3) RQ3: How can airlines achieve emission reductions at the lowest possible cost in the pursuit of carbon reduction targets? How can airlines achieve sustainable low-carbon development from the perspective of abatement costs?