MEASURING GLOBAL AIRLINE EFFICIENCY BY INCORPORATING INNOVATION CAPITAL, CO_2 EMISSIONS, AND CAPACITY UTILIZATION USING A DATA ENVELOPMENT ANALYSIS APPROACH

AZWAN BIN ABDUL RASHID

UNIVERSITI SAINS MALAYSIA

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by

AZWAN BIN ABDUL RASHID

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LIST OF ABBREVIATIONS

APEC	Asia-Pacific Economic Cooperation
ASK	Available Seat Kilometers
ASM	Available Seat Miles
ATK	Available Tonne Kilometers
CO_2	Carbon Dioxide
COVID-19	Coronavirus Disease of 2019
DDF	Directional Distance Function
DEA	Data Envelopment Analysis
DMUs	Decision Making Units
FATK	Freight Available Tonne Kilometers
FRTK	Freight Revenue Tonne Kilometers
FTE	Full-time Equivalent
gap-CI	Gap Capacity Inefficiency
GCI	Group Technology Capacity Inefficiency
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GTI	Group Frontier Technical Inefficiency
GTI	Group Technical Inefficiency
H-DEA	Hierarchical Data Envelopment Analysis
HDI	Human Development Index
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization

InCI	Innovation Capital Index
LPI	Logistic Performance Index
LTO	Landing/Take-off
MCI	Metatechnology Capacity Inefficiency
MDN-SBM	Meta Dynamic Network Slack-based Measure
MTI	Metatechnology Technical Inefficiency
MTOW	Maximum Take-off Weight
NCU	Network Capacity Utilization
OECD	Organisation for Economic Co-operation and Development
R&D	Research and Development
RAM	Range-adjusted Measure
RFTK	Revenue Freight Tonne Kilometers
RPK	Revenue Passenger Kilometers
RPM	Revenue Passenger Miles
RPM	Revenue Passenger Miles
RTK	Revenue Tonne Kilometers
RTK	Revenue Tonne Kilometres
SBM	Slack-based Measure
TGI	Technology Gap Inefficiency
TGR	Technology Gap Ratio
USD	United States Dollar

PENGUKURAN KECEKAPAN SYARIKAT PENERBANGAN GLOBAL MELALUI INTEGRASI MODAL INOVASI, PELEPASAN KARBON, DAN PENGGUNAAN KAPASITI DENGAN KAEDAH ANALISIS PENYAMPULAN DATA

ABSTRAK

Tesis ini mengkaji kecekapan, modal inovasi, dan kelestarian industri syarikat penerbangan global melalui tiga kajian yang saling berkaitan menggunakan kaedah analisis penyampulan data (DEA). Kajian pertama memperkenalkan kaedah DEA hierarki (H-DEA) berasaskan keberkesanan untuk membangunkan indeks modal inovasi (InCI) berdasarkan sampel 54 syarikat penerbangan global bagi tahun 2017. Hasil kajian mendapati bahawa, secara amnya, syarikat penerbangan mendedahkan tahap maklumat modal inovasi yang sederhana (skor purata analisis kandungan: 21.778). Namun, InCI menunjukkan masih terdapat ruang penambahbaikan yang besar, dengan purata potensi penambahbaikan sebanyak 48% (skor purata H-DEA: 0.520). Modal dalaman dikenal pasti sebagai faktor utama yang menyumbang kepada prestasi yang rendah, terutamanya di rantau yang mempunyai kadar pertumbuhan penduduk yang rendah seperti Oceania. Sebaliknya, syarikat penerbangan di Asia menunjukkan prestasi modal inovasi yang lebih kukuh. Struktur pemberat yang fleksibel dalam kaedah H-DEA membolehkan syarikat penerbangan memberi tumpuan kepada kategori modal inovasi yang paling kritikal, sekali gus menyediakan panduan strategik bagi penambahbaikan. Pendekatan sistematik ini membantu menangani jurang penyelidikan yang ketara dalam industri syarikat penerbangan global. Kajian kedua mengintegrasikan modal inovasi ke dalam rangka kerja DEA

rangkaian dinamik dua peringkat, melibatkan 29 syarikat penerbangan global yang beroperasi antara tahun 2016 hingga 2018. Model ini menilai kecekapan syarikat penerbangan dengan memisahkan operasi kepada peringkat pengeluaran dan peringkat perkhidmatan, sambil mengambil kira kesan bawaan antara tempoh masa. Hasil kajian menunjukkan bahawa skor kecekapan teknikal keseluruhan berada dalam julat 0.612 hingga 0.985. Syarikat penerbangan menunjukkan kecekapan yang lebih tinggi dalam peringkat pengeluaran (purata skor: 0.873) berbanding peringkat perkhidmatan (purata skor: 0.678), menandakan keperluan penambahbaikan yang lebih besar dalam prestasi jualan serta daya tarikan kepada penumpang dan kargo. Skor kecekapan juga menunjukkan variasi mengikut tahun, di mana tahun 2017 mencatatkan skor yang sedikit lebih tinggi berbanding 2016 dan 2018. Menariknya, skor modal inovasi yang tinggi tidak semestinya membawa kepada kecekapan teknikal yang lebih tinggi, menunjukkan kemungkinan berlakunya pelaburan berlebihan atau cabaran dalam pelaksanaan inovasi. Kajian ini menekankan peranan modal inovasi dalam mencapai kelebihan daya saing yang mampan dan menawarkan rangka kerja komprehensif untuk mengukur serta mempertingkatkan prestasi operasi. Kajian ketiga memberi tumpuan kepada penggunaan tenaga, pelepasan karbon, dan penggunaan kapasiti, dengan membandingkan kumpulan syarikat penerbangan dalam perikatan dan bukan perikatan menggunakan kaedah teknologi rangkaian berbilang produk dua peringkat yang diintegrasikan dengan rangka kerja sempadan meta tidak konveks. Kajian ini menggunakan sampel 33 syarikat penerbangan global bagi tahun 2018. Dengan menggabungkan analisis sempadan kumpulan dan sempadan meta, kajian ini mengenal pasti ketidakcekapan yang berpunca daripada teknologi kumpulan yang terhad, jurang teknologi, dan kapasiti yang tidak dimanfaatkan sepenuhnya. Hasil kajian menunjukkan bahawa ketidakcekapan teknikal dalam peringkat pengeluaran terutamanya berkaitan dengan penggunaan tenaga dan pelepasan karbon, manakala ketidakcekapan dalam peringkat jualan berpunca daripada kecekapan output yang rendah bagi hasil operasi dan hasil lain, serta penggunaan kapasiti yang lemah. Secara khusus, 12 syarikat penerbangan didapati beroperasi secara tidak cekap pada sempadan meta, manakala 6 syarikat penerbangan memerlukan pelarasan tenaga kerja bagi mengoptimumkan penggunaan kapasiti. Kajian ini mengemukakan strategi untuk meningkatkan kecekapan teknikal teknologi meta serta penggunaan kapasiti dalam rangkaian operasi. Secara keseluruhan, ketiga-tiga kajian ini memberikan pemahaman yang menyeluruh mengenai prestasi syarikat penerbangan global, dengan penekanan kepada modal inovasi, kecekapan operasi, dan kelestarian alam sekitar. Kaedah dan penemuan dalam tesis ini menawarkan panduan praktikal kepada pengurus, pembuat dasar, dan pengawal selia dalam menyokong keputusan strategik, pengagihan sumber yang optimum, serta memacu pertumbuhan mampan dalam industri syarikat penerbangan global yang sangat kompetitif.

MEASURING GLOBAL AIRLINE EFFICIENCY

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CO_2 EMISSIONS, AND CAPACITY UTILIZATION USING A DATA

ENVELOPMENT ANALYSIS APPROACH

ABSTRACT

This thesis examines the efficiency, innovation capital, and sustainability of the global airline industry through three interrelated studies utilizing advanced data envelopment analysis (DEA) frameworks. The first study introduces an effectiveness-based hierarchical DEA (H-DEA) method to construct an innovation capital index (InCI) using a sample of 54 global airlines in 2017. Findings reveal that while airlines generally disclose moderate levels of innovation capital information (mean content analysis score of 21.778), the InCI indicates a significant potential for improvement, with airlines, on average, having a 48% improvement opportunity (mean H-DEA score of 0.520). Internal capital was identified as the primary factor contributing to underperformance, particularly in regions with low population growth rates such as Oceania, while airlines in Asia demonstrated better innovation capital performance. The flexible weighting structure of the proposed H-DEA method enables airlines to target critical innovation capital categories, offering strategic insights for improvement. By providing a systematic approach to assessing innovation capital, this study addresses a significant research gap in the global airline industry. The second study extends this analysis by incorporating innovation capital into a two-stage dynamic network DEA framework using a sample of 29 global airlines operating between 2016 and 2018. This model evaluates airline efficiency by separating

operations into production stage and service stage while accounting for intertemporal carry-over effects. Results indicate that the overall technical efficiency scores of global airlines ranged from 0.612 to 0.985. Airlines generally showed higher efficiency in production stage (mean of 0.873) compared to service stage (mean of 0.678), highlighting a greater need for improvement in sales efforts and passenger/freight attraction. Efficiency scores also exhibit temporal variations, with 2017 showing slightly higher scores compared to 2016 and 2018. Notably, the presence of higher innovation capital scores did not consistently translate into greater technical efficiency, suggesting potential for excessive investment or risks in innovation integration. The study highlights the pivotal role of innovation capital in achieving a sustainable competitive advantage and offers a robust framework for measuring and improving performance across multiple operational stages. The third study focuses on energy consumption, CO_2 emissions, and capacity utilization, comparing alliance and non-alliance groups using a two-stage multiproduct network technology integrated with a nonconvex metafrontier framework, using a sample of 33 global airlines in 2018. By combining group frontier and metafrontier analyses, the study identifies inefficiencies arising from constrained group technologies, technology gaps, and underutilized capacities. Results reveal that technical inefficiencies in the production stage were primarily linked to energy and CO_2 emissions, while inefficiencies in the sales stage were attributed to low output efficiency of operating and other revenues, as well as low capacity utilization. Specifically, 12 airlines operate inefficiently at the constrained metafrontier, while 6 airlines require labor adjustments to optimize capacity utilization. Furthermore, significant differences in technical efficiency and technology gaps were observed between alliance and nonalliance airline groups, implying varied levels of constrained technology and performance potential across these operational structures. The study proposes strategies to improve metatechnology technical efficiency and network capacity utilization. Collectively, these studies provide a comprehensive understanding of airline performance by addressing innovation capital, operational efficiency, and environmental sustainability. The methodologies and findings offer actionable insights for managers, policymakers, and regulators to enhance strategic decision-making, optimize resource utilization, and promote sustainable growth in the highly competitive global airline industry.

CHAPTER 1

INTRODUCTION

1.1 Research Background

The airline industry is central to the rise of globalization and contributes enormously to global economic growth through tourism and trade. In 2018, the global airline industry served approximately 4 billion passengers and transported $6.7 trillion in goods to markets worldwide. The industry also generated 65 million jobs globally and contributed $2.7 trillion in gross domestic product (IATA, 2019). The International Air Transport Association (IATA) forecasts that by the end of 2034, global air travel demand will reach 7.3 billion passengers and double its economic impact, potentially creating 100 million jobs (IATA, 2020). Although the coronavirus disease 2019 (COVID-19) pandemic has had a severe impact on the expansion of the airline industry, on the basis of the significant growth experienced by the industry over recent decades, there are still positive signs for the future. By the end of 2023, it was forecasted that air travel demand in most regions would recover and surpass prepandemic levels (IATA, 2022).

As shown in Figure 1.1, IATA statistics from 2015 to 2023, along with estimates for 2024 and forecasts for 2025, highlight an industry of immense scale and remarkable resilience. Prior to the COVID-19 pandemic, global passenger traffic grew robustly, rising from 3.6 billion in 2015 to 4.5 billion in 2019. Freight volumes also saw significant growth, underscoring the industry's vital role in an increasingly interconnected world. Although the pandemic caused severe disruption, with sharp declines in 2020 and 2021, the sector has demonstrated a strong recovery. Forecasts project global passenger numbers not only to rebound to 4.3 billion in 2023 but also to exceed pre-pandemic levels, reaching 5.0 billion by 2025—driven by sustained high growth. At the same time, air freight continues to play a crucial role in global supply chains, showing both resilience and projected growth through 2025. This ongoing expansion, together with the industry's substantial contributions to employment and global GDP, firmly positions airlines as a critical engine of global economic activity and a key enabler of both human and commercial connectivity worldwide.

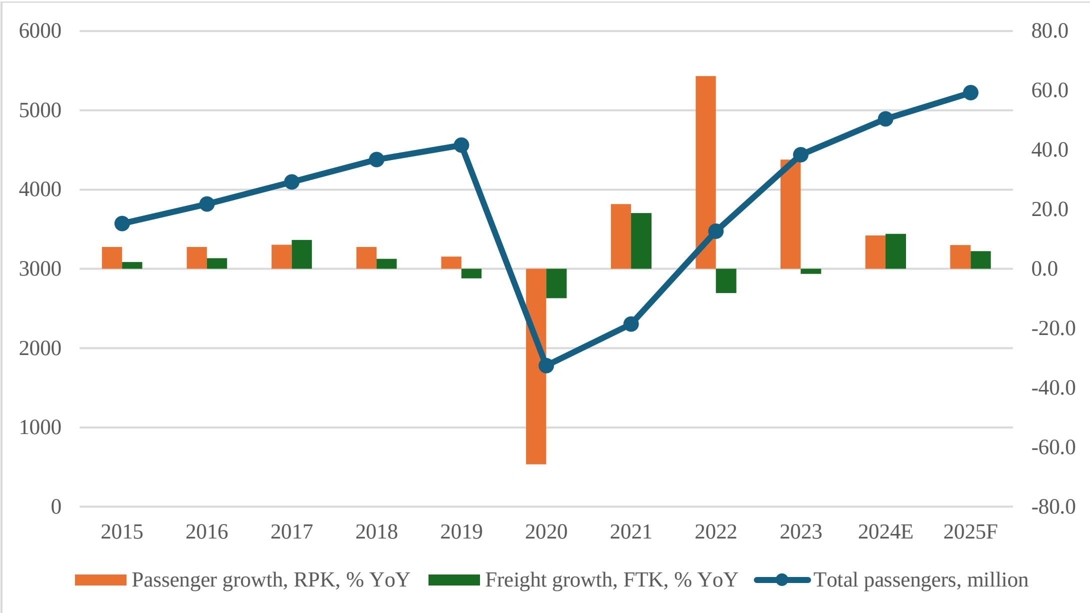

Figure 1.1 Passenger and freight traffic growth
Source: IATA Sustainability and Economics.

Despite a robust growth rate, the airline industry has experienced numerous changes in recent decades. The industry is struggling to keep the pace with a rapidly changing business environment that includes deregulation, economic recessions, intense competition, high fuel costs, technological change, digitalization, overcapacity, labour unrest, catastrophic events, infectious disease outbreaks and the emergence of low-cost carriers, which have affected the demand for air travel and disrupted operations. As such, the airline industry has found it difficult to achieve a sustainable competitive advantage. While several airlines have already gone out of business and/or merged, many airlines are operating with low profits (IATA, 2018).

In response to the challenging environment surrounding the airline industry, an increasing number of airline companies are focusing on innovation to increase their competitive positions (Franke, 2007). Innovation is widely regarded as an important means through which to achieve sustainability (Adams et al., 2016; Kuzma et al., 2020; Michelino et al., 2019) in a highly competitive and global economy (Chen et al., 2010; Kianto, 2011). Innovation is defined as a process involving multiple stages, where organizations transform ideas into new or improved products, services, or processes, helping them advance, gain a competitive edge, and stand out in their markets (Baregheh et al., 2009). In organizations' quest for economic, social and environmental sustainability, innovation is no longer an option but rather is essential for organizational viability.

It is apparent that regular measures such as cost-cutting exercises and efforts to create competitive operational platforms are inadequate for organizations to secure a sustainable competitive advantage. Therefore, it is of utmost importance that airlines implement innovative strategies that aim to strengthen their performance and are driven by new business models, efficiency improvement through technological innovation, and innovative business practices leading to the reshaping of market segments. As a result, innovation has become an important area of study within the discipline of airline research; for example, see Franke (2007), Halder (2013), Kamel (2006), Lee & Mo (2011), Liu et al. (2017), Nicolau & Santa-María (2012a, 2012b), Pereira et al. (2022) and Tinoco & Johnson (2010). The consideration of innovation capital is essential in airline efficiency studies since it plays a critical role in defining the dynamic operational performance of airlines.

The specific strategies for innovation and adaptation often exhibit significant regional variations. Airlines across different continents operate under distinct regulatory frameworks, face diverse market demands, and possess varying access to technological advancements and capital. For instance, well-established markets in North America and Europe might prioritize innovations in digital customer experience and sustainable aviation solutions driven by stringent environmental targets. In contrast, rapidly expanding aviation sectors in Asia and the Middle East might focus on optimizing network growth and large-scale operational efficiencies through technological integration. Recognizing these regional specificities in innovation drivers and outcomes is crucial for a comprehensive understanding of global airline performance and for designing effective strategies.

The airline industry also plays a significant role in the release of carbon dioxide (CO_2) emissions. To achieve CO_2 neutrality by 2050, the industry will continue to focus on addressing environmental issues and climate change. Graver et al. (2019) reported that between 2013 and 2018, CO_2 emissions from commercial airlines climbed almost 70% faster than projected by the United Nations and are expected to triple by 2050, accounting for one-quarter of CO_2 emissions from all sectors. Despite the significant decrease in air travel demand caused by COVID-19 restrictions, the global traffic level is expected to rebound by 2024 (IATA, 2020), resulting in a considerable amount of CO_2 emissions. Therefore, environmental concerns and climate change continue to be the industry's major obstacles and remain at the top of the agenda for the industry. IATA member airlines have pledged to achieve net-zero CO_2 emissions by 2050 to align with the goal of the Paris Agreement to reduce global warming.

Moreover, the airline industry is under intense pressure from governments and travelers to implement initiatives to reduce its environmental impact. At least 1.8 gigatonnes of CO_2 must be abated in 2050 to meet the demands of the 10 billion people projected to fly in that year (IATA, 2022). Another challenge is that reducing CO_2 emissions has financial implications; thus, striking a balance between environmental sustainability and financial sustainability is vital. As such, measuring airline productivity and efficiency is the best approach for enabling improvements in operational efficiency and reducing production costs. Consequently, a growing number of studies, such as Cui & Li (2019), Lee et al. (2017), Lee & Worthington (2014), and Scotti & Volta (2015), have examined the relationships between airline efficiency and environmental factors.

Capacity utilization is another important area of research that has attracted the interest of researchers in the past. This measure is commonly used in the literature to capture the output gap between actual and full capacity production. It sheds light on how well a decision-making unit (DMU) maximizes its available productive capacity to increase output while keeping production costs low. Capacity and capacity utilization are indicators of production capability that are defined through two broad approaches, a technological approach based on production possibilities and an economic approach based on optimizing firm behavior (Hickman, 1957). Capacity and capacity utilization are defined as the ratio of actual output to some reference output level and are typically considered short-term concepts that depend on the amount of physical capital (e.g., capital, technology) in use, unless stated otherwise. Capacity is wasted when output falls below the maximum producible output from the variable and fixed inputs used, while capacity is underutilized when variable input falls short of the amount needed to produce maximum output. Given that capacity and capacity utilization are essentially short-term concepts, they should be aligned with an airline's short-term goals.

1.2 Problem Statement

Although the global airline industry plays a vital role in economic connectivity and continually seeks competitive advantage, the absence of comprehensive, integrated frameworks to evaluate innovation capital, operational efficiency, and environmental sustainability simultaneously limits effective strategic decision-making and sustainable development. The airline industry faces a variety of challenges in developing approaches to reliably measure performance and improve airline efficiency and sustainability. In the current landscape, addressing the issues that are increasingly being utilized to investigate airline efficiency is essential. This section focuses on the following three primary issues: (a) measuring innovation capital performance; (b) measuring airline efficiency, which incorporates innovation capital; and (c) measuring airline efficiency, which simultaneously incorporates capacity utilization, energy consumption and CO_2 emissions.

1.2.1 Measurement for Innovation Capital Performance

Since the seminal work of Franke (2007), which examined innovation as a key driver of airlines aiming to obtain a competitive position, innovation has evolved into an important item on the airline research agenda. Innovation capital is defined as the resources, skills, and expertise an organization possesses that empower it to create, refine, and bring to market new ideas, products, services, processes, or business models. It forms a crucial part of a company's intellectual capital and plays a key role in securing and maintaining a competitive edge in the modern knowledge-driven economy (Edvinsson & Malone, 1997; Sveiby, 1997). Innovation has had a significant effect on the continuing profitability of airlines, helping them stay ahead of the competition and increasing their market value (Bowen et al., 2010; Nicolau & Santa-María, 2012a, 2012b). For example, airlines that strive for differentiation strategies need innovation to develop unique features that distinguish them from their competitors. Air Asia, JetBlue Airways and Japan Airlines are examples of airlines that have taken an unusual step by innovatively investing in start-up companies with the aim of bringing fresh ideas and creating new value to keep them one step ahead of their competitors. A recent study by Kuzma et al. (2020) revealed a significant positive relationship between innovation and organizational sustainability performance, thus confirming that innovation-oriented processes allow organizations to embrace innovative prospects to address the changing marketplace and consumer demand (Baregheh et al., 2009).

Given that innovation capital is critical for the airline industry, there is an increased need to understand its relevant categories, as doing so can provide knowledge about issues and concerns that can be easily understood and adopted. Evaluating the current state of innovation capital in the airline industry is essential for offering valuable insights that can assist managers in strengthening organizational innovation. While previous research has explored aspects of intellectual capital within the airline industry (e.g., Hamzah & Mohamed, 2010), there appears to be no existing study specifically focused on innovation capital, to the best of the author's knowledge. This gap in the literature is in broad contrast with the view of Lev (2001) that innovation is a catalyst of firm value. Furthermore, the issue of how to measure innovation capital is central to the development of innovation capital assets and the estimation of their effects on firm performance (Kaplan & Norton, 1996), which highlights the importance of measuring innovation capital information to support decision-making and improve the results. Therefore, this research addresses this gap by constructing an innovation capital index (InCI) for a sample of global airlines.

Owing to the extensive dissemination and accessibility of annual reports (Ahmed Haji & Mohd Ghazali, 2012; Yi & Davey, 2010), which serve as a primary channel for communicating information, including details on innovation (Elfeky, 2017), and the increasing significance of innovation in securing competitive advantages (Bellora & Guenther, 2013; Buenechea-Elberdin, 2017; Kuzma et al., 2020), annual reports are utilized to communicate innovation capital information to diverse sets of stakeholders. To evaluate innovation-oriented practices reported by airlines in their annual reports, a disclosure index serves as an effective proxy. This index encompass both quantitative and qualitative indicators. It is well-established that using a disclosure index with multidimensional categories facilitates a comprehensive quantitative content analysis of disclosure documents. Content analysis is a research tool used to codify text into specific themes by analyzing and quantifying the frequency with which each theme occurs (Krippendorff, 2018). A major challenge in the development of a disclosure index is the procedure used to measure and weight different items within subcategories so that they can be combined. One major shortcoming of content analysis is that it does not consider the data normalization process in the ranking exercise.

In content analysis, researchers often quantify the presence or frequency of specific elements within textual data—for example, counting innovation initiatives in annual reports. However, aggregating these counts into a composite index for ranking purposes introduces significant challenges due to the absence of data normalization:

(a) Disparate scales and magnitudes – different types of data, such as monetary values (e.g., R&D expenditures) and simple counts (e.g., number of partnerships), operate on vastly different scales. Without normalization, categories with larger numerical values can disproportionately influence the overall scores, irrespective of their relative importance to innovation capital.

(b) Size bias – larger organizations or those with more extensive reporting tend to generate higher raw counts. This can lead to misleading rankings, where larger airlines may appear more innovative merely because they disclose more information, rather than due to greater innovation efficiency or effectiveness.

(c) Lack of comparability – in the absence of a common measurement scale, direct and meaningful comparisons across entities (e.g., airlines) become problematic, as raw scores may fail to accurately represent true relative performance.

(d) Misleading rankings – consequently, the omission of normalization can result in rankings that inaccurately reflect the actual innovation capabilities or performance of the entities assessed.

By contrast, methods such as data envelopment analysis (DEA) inherently normalize data by adjusting all variables to a common scale. This process addresses issues related to varying magnitudes and organizational size, thereby enabling a more equitable, objective, and accurate ranking that reflects relative performance rather than mere disclosure volume. The objective of this research is thus to propose an effectiveness-based hierarchical data envelopment analysis (H-DEA) approach to endogenously assign weights with the purpose of aggregating the subcategories for the InCI. This index is subsequently used to conduct airline benchmarking by measuring the innovation capital of each airline in the following three subcategories: internal, external and human capital.

1.2.2 Airline Efficiency Measurement that Incorporates Innovation Capital

While capital in the form of tangible and financial assets is important to the airline industry, innovation has emerged as a key type of intangible capital. In the highly competitive and dynamic business landscape, airlines continue to leverage innovation capital to improve their efficiency and operational capabilities (Liu et al., 2017; Pereira et al., 2022; Tinoco & Johnson, 2010;), gain competitive advantages (Franke, 2007; Halder, 2013; Lee & Mo, 2011; Nicolau & Santa-María, 2012a, 2012b; Pereira et al., 2022) and achieve sustainability (Halder, 2013; Kamel, 2006; Kuzma et al., 2020; Pereira et al., 2022). The contribution of innovation capital to improving airline efficiency is significant. For example, Air New Zealand and Delta Airlines have implemented a biometric-enabled baggage drop to expedite the passenger check-in process and adopted the use of sustainable aviation fuel as a green technology with which to attain net-zero CO_2 emissions. These improvements are essential for airlines in enhancing their efficiency and operational capabilities as well as creating value, which opens new avenues for the growth of the airline industry. Airline efficiency measurement models that set aside innovation capital tend to overestimate or underestimate airlines' efficiency (Franke, 2007; Fagerberg, 2009), thus leading to inaccurate judgements and erroneous conclusions about airlines' overall performance.

Another unique feature of this study is the selection of innovation capital as a type of carry-over shared input. Innovation capital is intangible capital that is carried over to the subsequent period to address both current and future challenges. The decisions made in the current period regarding innovation capital affect the operational strategies and capacities of airlines to generate available capacity and passenger services in the subsequent period. Therefore, innovation capital is crucial for determining the dynamic operational performance of airlines, and furthermore, owing to the difficulty in allocating innovation capital to a particular subprocess, it is more suitable to treat innovation capital as carry-over shared input between subprocesses. Therefore, this study aims to analyze the efficiency of global airlines by incorporating innovation capital into a two-stage dynamic network data envelopment analysis (DEA) framework comprising production and service stages over a 3-year period between 2016 and 2018.

Efficiency measurement is an essential task that offers managers and decision-makers a holistic perspective from which to increase operational efficiency and reduce production costs. As such, interest in measuring efficiency has attracted significant attention among academics and industry analysts in the last few decades. The DEA method has been widely applied to measure the relative efficiency of DMUs in various industries, including agriculture (Fei & Lin, 2016), banking (Duygun et al., 2016b), fisheries (Lee & Midani, 2015), hospitals (Karagiannis, 2015), manufacturing (Yang et al., 2019), ports (Nguyen et al., 2018), education (Thieme et al., 2013), textiles (Lin & Zhao, 2016), and water services (Molinos-Senante et al., 2017). Similarly, owing to the challenging environment surrounding the airline industry and its highly regulated nature, it is not surprising that there is a significant body of literature devoted to measuring airline efficiency using the DEA method, highlighting the emerging interest in this field.

The traditional DEA method treats each airline as a DMU with multiple inputs and outputs, and only aggregate efficiency is considered when airline efficiency is evaluated. However, the traditional DEA method does not allow researchers to identify the efficiency of the subprocesses, the internal structure of the DMUs and the intertemporal efficiency changes within the system. While numerous studies have evaluated the intertemporal performance of airlines using the Malmquist productivity index or window analysis, they have disregarded the transitional elements that exist in airline operations, leading to biased efficiency assessments and thus providing misleading information to DMUs. In a dynamic environment, airlines exhibit carry-overs, such as capital stock and fleet size, that can be transferred from one period to the next. Several researchers have employed dynamic network DEA to model the intertemporal characteristics of these transition elements, considering the carry-over in airline efficiency studies including dynamic network DEA (Omrani & Soltanzadeh, 2016; Yu et al., 2017; Yu et al., 2019; Zhang & Zhang, 2021), dynamic network slacks-based measure (SBM) (Losa et al., 2020; Lahouel et al., 2022), meta dynamic network SBM (Chou et al., 2016), and fuzzy dynamic network DEA (Soltanzadeh & Omrani, 2018). In this study, the dynamic network DEA model is used to evaluate airline efficiency across multiple periods using innovation capital as a carry-over variable simultaneously.

Given that the airline industry is capital intensive, many dynamic network DEA studies examining airline efficiency have used the number of fleet seats (Omrani & Soltanzadeh, 2016; Soltanzadeh & Omrani, 2018); the amount of investment in assets (Losa et al., 2020); total assets (Zhang & Zhang, 2021); and property, plant and equipment (Lahouel et al., 2022) as carry-over variables or dynamic factors. Other studies have utilized the number of accidents (Chou et al., 2016), the size of self-owned fleets and waypoints (Yu et al., 2017), and the number of destinations (Yu et al., 2019). However, no airline efficiency studies have considered innovation capital as a carry-over variable. This omission is in broad contrast to the view that innovation capital plays a significant role in improving efficiency in the airline industry (Edvinsson & Malone, 1997; Pereira et al., 2022). In this study, an airline's amount of innovation capital, as measured by the disclosure score, can be used as a carry-over shared input that affects not only the current period but also subsequent periods. To the best of the authors' knowledge, this is the first study to integrate innovation capital into the global airline efficiency context.

1.2.3 Airline Efficiency Measurement Simultaneously Incorporating Capacity Utilization, Energy Consumption and CO_2 Emissions

Although numerous studies have addressed airline productivity and efficiency and include CO_2 emissions as an undesirable output, thus far, no studies have simultaneously considered capacity utilization, energy consumption, and CO_2 emissions in the airline industry. In contrast to the literature, the proposed framework integrates capacity utilization constraints into a two-stage multiproduct network technology, resulting in a best-practice technology comprising airlines with similar capacities. Over the last two decades, a significant number of airline efficiency studies have employed the load factor as a proxy for capacity utilization to analyze the determinants of airline inefficiency. However, there have been limited studies on airline efficiency that include capacity utilization as a measure, with Coelli et al. (2002) and Yu et al. (2016) being among the few that have focused more on technical efficiency. The key objective of addressing environmental issues is to prioritize environmental sustainability and ensure that environmental considerations are fully integrated into the operational performance of airlines. Moreover, considering the nonstorable nature of intermediate outputs in the aviation industry, it is crucial to have a reasonable measure of capacity utilization that takes into account environmental factors and the current level of inputs. However, the existing methods for measuring capacity utilization in airlines overlook the presence of two-stage production processes and undesirable outputs.

In conventional airline efficiency measurements, sample selection is assumed to involve homogeneous technology. However, this assumption often does not hold due to the expansion of the global airline industry over the last two decades. One airline classification in the literature divides the airline sample into alliance and nonalliance groups, mainly due to the significant role played by airline alliances in the industry and their impact on travel offerings. Consequently, when considering airline efficiency, it is necessary to account for the potential technology heterogeneity that exists between airline alliance and nonalliance groups. Since the first global alliances were established more than 25 years ago, several airline efficiency studies—e.g., Oum et al. (2005), Barros & Peypoch (2009), Sjögren & Söderberg (2011), Yakath Ali & See (2023), and Yu & See (2023)—have been conducted to compare airline performance between alliance and nonalliance groups. However, the contribution of alliances to airline performance is inconclusive.

Ideally, airlines' ability to reduce their levels of energy consumption and CO_2 emissions is often over- or underestimated by efficiency measurement models that do not capture the effect of capacity utilization rates. Operating flights with underutilized capacity—such as many empty seats or unused cargo space—results in disproportionately higher energy consumption and CO_2 emissions per passenger or per unit of cargo. Aircraft consume a substantial amount of fuel simply to complete a flight, irrespective of load factor. Consequently, inefficiencies in capacity utilization increase the environmental impact per unit of output, as the fixed energy cost is distributed over fewer revenue-generating units. Conversely, improving capacity utilization allows airlines to transport greater volumes of passengers or cargo with a relatively constant energy input, thereby reducing CO_2 emissions per unit and enhancing overall environmental efficiency. These inaccurate estimations raise the question of whether capacity utilization inefficiency increases energy and CO_2 emissions and decreases final outputs. To capture the technological heterogeneity between alliance and nonalliance groups, a single common frontier framework may not be appropriate and can lead to serious bias in the estimates. To the best of the authors' knowledge, this is the first study that shows the simultaneous effect of capacity utilization, energy and CO_2 emissions in global airlines using a two-stage multiproduct network technology with a nonconvex metafrontier framework.

This study evaluates the degree to which a multiple-input–output process deviates from its maximum capacity when operating within a two-stage multiproduct network technology, followed by a decomposition of the capacity inefficiency into two components, i.e., technical and capacity utilization inefficiencies. This study focuses on assessing the contribution of unutilized capacity to production efficiency; each airline has surplus capacity since it does not fully utilize its capital (i.e., the underproduction of final goods) relative to the size of its labor force and ideally selects intermediate products. Therefore, airlines can extend their final products to attain greater technological efficiency and then expand further to reach their target capacities.

Several DEA or network DEA capacity measures have been empirically applied to measure the regional production potential of Chinese provinces (see Yan et al., 2019) and the societal welfare of 47 Japanese prefectures (see Fukuyama et al., 2020). Despite limited samples, the empirical evidence indicates that DEA-based capacity concepts can effectively account for the multiple goals of DMUs when both environmental and economic goods are improved, such as those monitored by the

Organization of Economic Cooperation and Development (OECD). Although this study adopts Fukuyama et al.'s (2020) framework, the empirical model established using network technology, which incorporates a capacity utilization constraint and directly links energy and CO_2 emissions through a costly disposability assumption, can offer effective managerial suggestions for airline management.

1.3 Research Questions

This study aims to address the following research questions:

i. How can an InCI be developed and utilized to measure and benchmark innovation capital performance for the global airline industry?

ii. How does the incorporation of innovation capital influence the two-stage dynamic network efficiency of the global airline industry?

iii. How can the two-stage multiproduct network efficiency of global airlines be assessed while simultaneously accounting for the effects of capacity utilization, energy consumption, and CO_2 emissions within a nonconvex metafrontier framework?

1.4 Research Objectives

This study focuses on the following objectives:

i. To develop an InCI for the global airline industry using an effectiveness-based H-DEA approach.

ii. To analyze the efficiency of the global airline industry by incorporating innovation capital into a two-stage dynamic network DEA framework.

iii. To examine the simultaneous effects of capacity utilization, energy consumption and CO_2 emissions of global airlines using a two-stage multiproduct network technology with a nonconvex metafrontier framework.

1.5 Study Significance

For the first objective, this study contributes to the literature in the following manner: (a) the effectiveness-based H-DEA method offers an alternative technique to objectively compute diverse weights for innovation capital subcategories along with a robustness check for the InCI. As such, the method facilitates the process of endogenously assigning weights with the purpose of aggregating the subcategories for the InCI, and (b) the weights obtained for each subcategory can be used to describe the extent of the improvement needed to enhance innovation capital performance. This index is then utilized to develop a benchmark for airlines by measuring the innovation capital subcategories of each airline in the three selected categories, namely, internal, external and human capital. The results allow airlines to select those relevant innovation capital subcategories that they want to improve to enhance their innovation capital performance.

For the second objective, this study is one of the first studies to integrate innovation capital into the context of global airline efficiency. This study contributes to the literature by introducing innovation capital as a new carry-over shared input, together with other inputs/outputs, in a dynamic network structure and considers the internal component processes. In this study, the calculated technical efficiency score and endogenous weights provide a basis on which airlines can identify operational inefficiencies at the production and/or service stages to remain competitive in the market. Therefore, airline managers and regulators can benefit from a comprehensive comparative analysis of major global airlines' efficiency. This study can also assist airlines and public agencies in developing appropriate efficiency measures for effective resource planning and management as well as for the sustainable development of the airline industry.

Finally, regarding the third objective, this study contributes to the current body of knowledge in the following three ways: (a) metatechnology is combined with group-specific multiproduct network technology to attain an all-inclusive metafrontier without the need to separately evaluate the technical efficiency of both multiproduct network technologies, (b) all possible group-specific frontiers can serve under the umbrella (upper or lower) of the metafrontier of multiproduct network technology, and (c) two subprocesses are provided by the improved technique within the network production structure to decompose the DMUs with limited capacity into technical and capacity utilization inefficiencies. Thus, a DMU's technical inefficiency (hereafter, energy and emission inefficiency in the production process and final output in the sales process) and network capacity utilization can be reduced by identifying suitable yardsticks in the estimation of the two subprocesses. Such an investigation, to the best of available knowledge, is undocumented in the literature.

1.6 Study Scope

The scope of this study is restricted to global passenger airlines that operate both internationally and domestically. The airline sample is selected based on Skytrax, a United Kingdom-based organization founded in 1989 that is a leading authority on airline and airport quality assessment. Skytrax is best known for its World Airline Awards and its airline star rating system, both of which are based on global passenger satisfaction surveys and independent quality audits. These surveys gather feedback from millions of travelers on aspects such as cabin service, seating, entertainment, and airport facilities, while the audits assess up to 800 criteria per airline using standardized research methods. Although concerns have been raised about transparency, Skytrax remains a credible benchmarking entity widely cited by both airlines and consumers. While it does not explicitly measure innovation, its evaluation framework indirectly captures it through categories such as service enhancements, digital tools, and sustainability initiatives, making it a valuable source for assessing innovation-related performance in the airline industry.

This study focuses exclusively on full-service airlines, excluding low-cost airlines due to fundamental differences in their business models and data, which would introduce variability and complicate efficiency comparisons using DEA. Key reasons for exclusion include:

(a) Business model differences – full-service airlines offer complex services with multiple cabin classes and extensive amenities, operating hub-and-spoke and long-haul routes, while low-cost airlines prioritize cost reduction with simple point-to-point routes, single-class seating, and unbundled services.

(b) Innovation focus – full-service airlines innovate to enhance service differentiation and network efficiency, whereas low-cost airlines focus on cost-saving and operational simplicity. Combining them could obscure these distinct innovation drivers.

(c) Data incompatibility – financial and operational data differ significantly between full-service airlines and low-cost airlines in scope and reporting, risking compromised analysis if merged.

(d) Research alignment – the study's focus on innovation, efficiency, and sustainability aligns with full-service airlines' complex operations; including low-cost airlines would require different variables and broaden the study beyond its scope.

To ensure the homogeneity of the DMUs and the comparability of the results, this study focuses exclusively on full-service airlines, acknowledging that the findings may not be directly generalizable to the low-cost carrier segment without further dedicated research.

The data for this study were drawn from the period between 2016 and 2018 for two main reasons. First, at the time of data collection, this interval represented the most recent and comprehensive set of publicly accessible annual reports for the global airlines included in the sample. Second, and more importantly, this timeframe enabled the analysis to capture typical operational and innovation patterns within the airline industry, deliberately excluding the unprecedented disruptions caused by the COVID-19 pandemic beginning in early 2020. Incorporating data from 2020 onward would have introduced significant external shocks—such as travel restrictions and widespread operational suspensions—that would distort efficiency and innovation capital assessments, thereby complicating the evaluation of airline performance under normal conditions.

For the first research objective, the sample in this study includes 54 of the World's Best 100 Airlines based on the 2018 Skytrax World Airline Awards, with 2017 as the focal year. This objective is centred on the development of an InCI for the global airline industry using an effectiveness-based H-DEA approach. The data on innovation capital contained in the annual reports are compiled from all airlines operating globally, which comprise international, domestic, and cargo operations. Therefore, the information pertaining to innovation capital provided in the annual reports is relevant for this study. For the second objective, the scope of this study is restricted to 29 global full-service airlines on the basis of the World's Best 100 Airlines as indicated by the Skytrax World Airline Awards in 2018 and that operated between 2016 and 2018. This timeframe is selected to ensure the most comprehensive collection of publicly available data, i.e., annual reports at the time of the data collection process. The following four input variables are included in the airline production subprocess: fuel cost, maximum takeoff weight (MTOW), number of employees and maintenance costs. Available tonne kilometers (ATK), as an intermediate variable combined with ticketing and promotion costs, is used as input in the airline service subprocess to generate revenue passenger kilometers (RPK) and revenue freight tonne kilometers (RFTK). The measurement model also considers innovation capital and MTOW as the carry-over shared input and carry-over input, respectively. The objective of this approach is to analyze global airline efficiency by incorporating innovation capital into a two-stage dynamic network DEA model.

The third objective involves examining the relationships between network capacity utilization and energy and CO_2 emissions inefficiencies in the alliance and nonalliance groups. The sample consists of 33 global airlines operating in 2018. The dataset comprises three input variables, fleet size, employees, and fuel; two intermediate variables, RPK and RFTK; and three output variables, operating revenue, other revenue, and CO_2 emissions. The objective of this investigation is to evaluate the energy and emissions, as well as the capacity utilization and inefficiencies of global airlines in the alliance and nonalliance groups. This aim is accomplished by employing a two-stage multiproduct network technology with a nonconvex metafrontier framework.

1.7 Research Process

The research processes as outlined in Figure 1.2 are carefully designed and implemented to ensure that all research objectives are systematically addressed and achieved, ensuring a coherent and rigorous approach to the investigation.

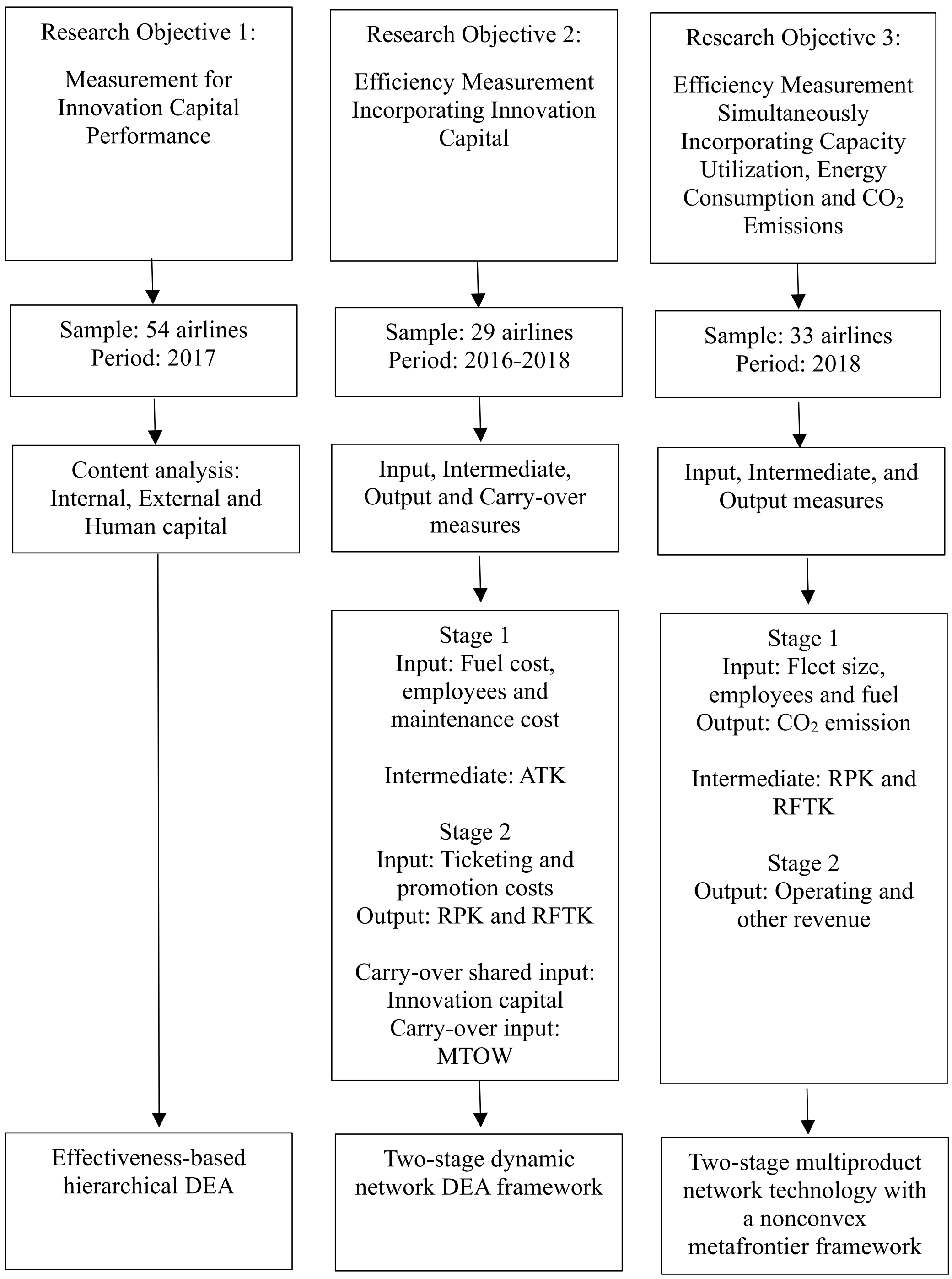

Figure 1.2 Research framework

1.8 Thesis Structure

The remainder of the thesis is structured as follows. In Chapter 2, the relevant literature on innovation capital, dynamic network DEA and multiproduct network technology with a nonconvex metafrontier framework related to airline performance is reviewed. Drawing upon this comprehensive review, the sample, data and methodology used in the study, including the effectiveness-based H-DEA, the two-stage dynamic network DEA structure that incorporates innovation capital, and the two-stage multiproduct network technology with a nonconvex metafrontier framework that simultaneously considers network capacity utilization and energy and CO_2 emissions inefficiencies, are proposed in Chapter 3. Chapters 4, 5 and 6 present the empirical findings of the study, while managerial implications, limitations and recommendations for future studies are presented in the final chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter addresses the concepts, theories and empirical studies pertaining to innovation capital and airline efficiency and is structured into three primary sections. Section 2.2 introduces the conceptualization and theoretical foundation of innovation capital. Section 2.2.1 discusses innovation capital in the airline industry, and Section 2.2.2 provides approaches to measuring innovation capital. Section 2.2.3 introduces the innovation capital measurement utilizing the effectiveness-based H-DEA method. Section 2.3 elaborates on the conceptualization and theoretical foundation of the efficiency measures. Section 2.3.1 analyzes prior research on airline efficiency. Sections 2.3.2 and 2.3.3 outline the analysis of airline efficiency measurements using two-stage dynamic network DEA and two-stage multiproduct network technology. A summary of the chapter is provided in Section 2.4.

2.2 Concept and Theory of Innovation

The relationship between innovation and business success has been a central theme in economic research for centuries. Early economic thinkers such as Adam Smith (1776) acknowledged the importance of technological progress, while Karl Marx (1858) emphasized its transformative power in society. Alfred Marshall (1920) further highlighted knowledge as a crucial driver of economic growth. These foundational perspectives established innovation as a key catalyst for economic change—a concept later formalized and expanded by Joseph Schumpeter, whose work has deeply shaped contemporary innovation theory (Freeman & Soete, 1997).