FINANCIAL AND ENVIRONMENTAL SUSTAINABILITY ANALYSIS

CRITERIA FOR EVALUATING THE AEROTROPOLIS DEVELOPMENT

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Provas destinadas à obtenção de grau de Mestre em Operações de Transporte Aéreo

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Criteria for evaluating the aerotropolis development

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RESUMO

Esta dissertação investiga a interação entre a sustentabilidade financeira e ambiental no modelo de aerotropolis, com foco nos principais aeroportos que gerem mais de 40 milhões de passageiros anualmente. Utilizando uma combinação de Análise de Envolvimento de Dados (DEA) e análise SWOT, a pesquisa avalia a eficiência das medidas de sustentabilidade e os seus impactos no desempenho operacional e financeiro. O estudo abrange dados de 2018 a 2023, excluindo os anos de pandemia de 2020 e 2021, para garantir insights confiáveis.

Os resultados revelam padrões diversificados de eficiência entre os aeroportos, com os mais eficientes beneficiando-se de políticas de sustentabilidade proativas e da priorização estratégica de metas ambientais. Estes aeroportos integram medidas como a adoção de energias renováveis, redução de resíduos e iniciativas de neutralidade carbónica nas suas operações, demonstrando uma ligação clara entre estruturas robustas de sustentabilidade e melhores resultados operacionais. Por outro lado, os aeroportos com pontuações de eficiência mais baixas enfrentam desafios como infraestruturas desatualizadas, restrições financeiras e objetivos estratégicos desalinhados, evidenciando áreas que necessitam de melhorias específicas.

Os contextos regulatórios emergem como influenciadores cruciais, com aeroportos em regiões regidas por políticas ambientais rigorosas a alcançarem maior eficiência. Estes resultados sublinham a importância de quadros regulamentares coesos e da harmonização de políticas globais no avanço das iniciativas de sustentabilidade. No entanto, os elevados custos iniciais de implementação e as políticas internacionais inconsistentes permanecem como barreiras significativas à adoção generalizada de práticas sustentáveis.

O estudo contribui para a literatura ao introduzir o modelo Environmental and Financial Sustainability Impact on Aerotropolis Model (EFSI.OAM), que fornece uma estrutura abrangente para avaliar o impacto dual da sustentabilidade nos resultados ambientais e financeiros. As recomendações incluem alinhar incentivos regulamentares com estratégias operacionais, fomentar avanços tecnológicos e promover a colaboração entre partes interessadas para alcançar um crescimento equilibrado.

Esta pesquisa destaca a necessidade de integrar considerações ambientais no planeamento financeiro e operacional para assegurar a viabilidade a longo prazo do modelo de aerotropolis. Ao abordar ineficiências e aproveitar oportunidades, os aeroportos podem alcançar um desenvolvimento sustentável, atendendo às exigências de um setor da aviação global em rápida evolução.

Palavras-Chave

Sustentabilidade; Finanças; Desenvolvimento Aeroportuário; Ambiente; Aerotrópolis

ABSTRACT

This dissertation investigates the interplay between financial and environmental sustainability within the aerotropolis model, focusing on major airports managing over 40 million passengers annually. Employing a combination of Data Envelopment Analysis (DEA) and SWOT analysis, the research evaluates the efficiency of sustainability measures and their impacts on operational and financial performance. The study encompasses data from 2018 to 2023, excluding the pandemic years of 2020 and 2021 to ensure reliable insights.

The findings reveal diverse efficiency patterns across airports, with consistently high performers benefitting from proactive sustainability policies and strategic prioritization of environmental goals. Efficient airports integrate measures such as renewable energy adoption, waste reduction, and carbon neutrality initiatives into their operations, demonstrating a clear link between robust sustainability frameworks and improved operational outcomes. Conversely, airports with lower efficiency scores face challenges such as outdated infrastructure, financial constraints, and misaligned strategic objectives, highlighting areas for targeted improvement.

Regulatory environments emerged as critical influencers, with airports in regions governed by rigorous environmental policies achieving higher efficiency. These findings underscore the importance of cohesive regulatory frameworks and global policy harmonization in advancing sustainability initiatives. High initial implementation costs and inconsistent international policies, however, remain significant barriers to the widespread adoption of sustainable practices.

The study contributes to the literature by introducing the Environmental and Financial Sustainability Impact on Aerotropolis Model (EFSI.OAM), which provides a comprehensive framework for evaluating the dual impact of sustainability on environmental and financial outcomes. Recommendations include aligning regulatory incentives with operational strategies, fostering technological advancements, and promoting stakeholder collaboration to achieve balanced growth.

This research highlights the necessity of integrating environmental considerations into financial and operational planning to ensure the long-term viability of the aerotropolis model. By addressing inefficiencies and leveraging opportunities, airports can achieve sustainable development while meeting the demands of a rapidly evolving global aviation landscape.

Keywords

Sustainability; Finance; Airport Development; Environmental, Aerotropolis.

RESUMO ALARGADO

INTRODUÇÃO

A dissertação investiga a sustentabilidade financeira e ambiental no modelo de aerotropolis, com foco em aeroportos que movimentam mais de 40 milhões de passageiros anualmente. Através de uma análise de eficiência utilizando a Análise por Envoltória de Dados (DEA) e uma análise SWOT complementar, o trabalho avalia como as medidas de sustentabilidade impactam os resultados financeiros e operacionais. Este estudo enfatiza a necessidade de equilíbrio entre viabilidade ambiental e financeira para o desenvolvimento sustentável dos aeroportos, destacando os desafios e as oportunidades presentes no setor.

ENQUADRAMENTO

O conceito de aerotropolis tem evoluído como um modelo de desenvolvimento urbano centrado em grandes aeroportos, que atuam como motores económicos e logísticos. Contudo, a sustentabilidade revela-se como um dos principais desafios, dado o impacto ambiental significativo da indústria da aviação. Este estudo contextualiza o tema numa era em que as preocupações ambientais estão no centro das discussões globais. A investigação está alinhada com meta de neutralidade carbónica para 2050, explorando como as iniciativas sustentáveis podem influenciar a eficiência operacional e financeira.

DESCRIÇÃO DO PROBLEMA E OBJETIVOS DA INVESTIGAÇÃO

O problema principal aborda como as medidas de sustentabilidade impactam a dinâmica financeira dos aeroportos e quais fatores contribuem para as variações observadas. Os objetivos específicos incluem:

1. Avaliar o impacto das medidas sustentáveis na rentabilidade dos aeroportos.
2. Examinar o papel das regulamentações nacionais na implementação de práticas sustentáveis.
3. Investigar os motivos para a não adoção de medidas sustentáveis.
4. Analisar as implicações comerciais da ausência de iniciativas sustentáveis.
5. Identificar estratégias bem-sucedidas de sustentabilidade nos aeroportos.

A metodologia combina a análise quantitativa via DEA e uma abordagem qualitativa com análise SWOT para uma compreensão mais ampla dos desafios e oportunidades.

PRINCIPAIS CONTRIBUIÇÕES

Os resultados destacam:

- Aeroportos localizados em regiões com regulações mais rigorosas frequentemente alcançam eficiência superior, sugerindo o impacto positivo de políticas proativas.
- Investimentos em iniciativas de sustentabilidade apresentam custos iniciais elevados, mas resultam em benefícios de longo prazo, como reputação aprimorada e eficiência operacional.
- A incorporação da sustentabilidade como prioridade estratégica é determinante para melhorias consistentes de eficiência.

O modelo EFSI.OAM ("Environmental and Financial Sustainability Impact on Aerotropolis Model") foi desenvolvido para avaliar a eficiência de aeroportos em termos ambientais e financeiros.

PRINCIPAIS CONCLUSÕES

A pesquisa conclui que, embora as medidas sustentáveis sejam essenciais para o futuro das aerotropolis, elas apresentam desafios financeiros significativos no curto prazo. Os aeroportos em locais com regulações mais rigorosas tendem a apresentar melhor desempenho, indicando a importância de políticas consistentes e incentivos globais. Além disso, os resultados evidenciam a necessidade de integração entre metas ambientais e operacionais para garantir um desenvolvimento equilibrado e com retornos.

PERSPETIVAS DE INVESTIGAÇÃO FUTURAS

Investigações futuras poderiam explorar:

1. Análises específicas sobre o impacto das tecnologias verdes na eficiência dos aeroportos.
2. Estudos comparativos entre aeroportos de diferentes tamanhos para avaliar as melhores práticas globais.
3. Desenvolvimento de modelos preditivos que integrem variáveis económicas e ambientais.
4. Avaliação do impacto da conscientização do consumidor sobre a procura por aeroportos sustentáveis.

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ABBREVIATIONS AND ACRONYMS.

ACA – Airport Carbon Accreditation

AMS – Amsterdam Airport Schiphol

BCN – Josep Tarradellas Barcelona–El Prat Airport

BCC – Variable Returns to Scale

BOS – Boston Logan International Airport

CCR – Constant Returns to Scale

DEA – Data Envelopment Analysis

DMU – Decision-Making Unit

EFSI.OAM –

FRA – Frankfurt am Main Airport

GRU – Governador André Franco Montoro International Airport

HKG – Hong Kong International Airport

HND – Tokyo International Airport

IST – İstanbul Havalimanı Airport

ISEC – Instituto Superior de Ensino e Ciência

PAXs – Passengers

SIN – Singapore Changi Airport

SWOT- Strengths, Weaknesses, Opportunities, Threats

SYD – Kingsford Smith International Airport

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1. INTRODUCTION

1.1. GENERAL

Aerotropolis is a concept that is evolving over time, and in the future, major airports will be considered aerotropolises with developments progressing towards this. These hubs are becoming key players in connecting people, goods, and businesses across the globe, making them essential for economic growth (Kasarda & Appold, 2014). Although this concept is very attractive for a country's economy, in terms of sustainability, it seems like a significant challenge. With this in mind, I aim to explore whether sustainable aerotropolises are possible.

The primary focus is on assessing whether sustainability measures have a direct impact on airport profitability. Additionally, the study aims to explore the reasons why some airports may not adopt sustainable practices, potentially due to associated costs. These might include the high investments required, limited regulatory demands in some regions, or even a lack of immediate financial benefits. The investigation also researches the repercussions of not being recognized as a sustainable airport and how it influences business dynamics, such as losing competitive advantages, stakeholder confidence, and customer preference.

This topic is important for the field since the significance of sustainability in the world has increased, and the field represents a significant portion of the CO_2 emissions worldwide. This makes it critical for all parties involved to take action. The aviation industry alone is responsible for over 2% of global emissions, which is projected to increase (Ansell & Harn. 2020). This highlights how necessary it is for airports to find effective ways to align with environmental goals while maintaining their operational and financial viability.

1.2. MOTIVATION

By 2050, we're aiming to drastically reduce carbon emissions to protect our planet (Chen, 2021). This goal is crucial for our future. One big contributor to carbon emissions is the aviation industry (Ansell & Harn. 2020). As more people travel by air, it's important to find ways for airports to grow while being kind to the environment.

That's where the idea of sustainable aerotropolises comes in. It's about making airports more eco friendly while still helping economies thrive. These changes could include things like using renewable energy, improving waste management systems, and making infrastructure more

energy efficient. I'm interested in exploring if this idea can really work, especially as more cities look to aerotropolises as a way to boost their economies and create jobs.

The Carbon 2050 targets remind us that we need to act fast. I believe looking into sustainable airports is one way to make a difference. By studying this topic, I hope to find ways to make airports greener and more efficient, while also being financially sustainable.

To sum up, I'm excited to dive into this research because I believe it can help make air travel better for our planet. Understanding how sustainability can be part of airport growth is essential for ensuring a brighter and more responsible future for everyone.

1.3.SCOPE

In the air transport operations industry, the concept of sustainable aerotropolises has emerged as an important point of questioning. This study aims to explore the viability of this concept in the future by investigating the impact of implementing sustainability measures on airports' financial reports.

The scope of the study is limited as it specifically focuses on the concept of sustainable aerotropolises within the air transport operations industry and aims to assess its future viability by examining major airports worldwide. These are airports that manage over 40 million passengers annually and represent the largest contributors to global aviation trends. However, focusing on these airports means that smaller airports or regional hubs are not part of this study, which may affect the generalizability of the findings.

The scope also considers that data from 2020 and 2021 was excluded, as these years were heavily impacted by the COVID-19 pandemic, which disrupted usual airport operations and distorted financial and operational results. By doing this, the study ensures that the analysis reflects normal operational conditions, offering a more reliable perspective on sustainability's impact on airport efficiency and profitability.

1.4.OBJECTIVES

The general objective of this study is to assess the viability of sustainable aerotropolis around the world since this is a concept that is growing over time with more countries interested in having one to develop their economy even further. In order to get to a conclusion first the specific objectives have to be evaluated such as:

- How sustainability measures impact on profitability

- Examine the effect country regulation has on airports' implementation of sustainability measures.
- How to investigate the reason for the non-adoption of sustainable practices
- How to analyse the business implication of airports not adopting sustainable measures
- How to identify airports' successful strategies in sustainability

1.5. METHODOLOGY

A mix approach, so a quantitative and a qualitative approach, is the most effective method to obtain comprehensive insights into the relationship between sustainability measures and airport financial performance. The methodology involves a diverse data collection process such as financial reports, sustainability reports and airport accreditations such as Airport Carbon Accreditation. A deductive method will be used in this research since hypotheses are being set and will be tested out in this study. The quantitative approach which will be DEA, demonstrated in detail on subsection 3.5, allows for the analysis of a large sample size, enabling a wide comparison of variables. Numerical representation facilitates the identification of trends and patterns, contributing to a clearer understanding of the relationship between sustainability and financial performance. The qualitative approach which will be a SWOT analysis, as explained in detail in subsection 3.7, will allow to find opportunities for development.

This study will be an extensive case study since it will be an analysis of large data set from different airports around the world. It will rely on a robust dataset sourced from financial and sustainability reports for 2018, 2019, 2022 and 2023 for various airports. The data includes key indicators such as EBITDA, passenger numbers, aircraft movements and sustainability metrics. Specific accreditations, like Airport Carbon Accreditation, will be noted to measure the level of sustainability initiatives at each airport. We'll meticulously compile a comprehensive dataset, capturing the sustainability and financial performance of each airport over distinct time frames. This compilation will serve as a valuable resource for in-depth data analysis and will be collected from airport official websites and company group websites in case the airport is part of a group.

1.6. WORK STRUCTURE

This dissertation is organized into five main chapters, each systematically addressing different aspects of the study to provide a comprehensive understanding of the relationship between

financial and environmental sustainability within the aerotropolis model. The structure of the dissertation is as follows:

Chapter 1: Introduction

The introductory chapter provides the context and rationale for the research. It begins with an explanation of the evolving aerotropolis concept and its importance in modern urban and economic planning. The chapter highlights the challenges of integrating sustainability into airport operations and introduces the primary research question: How do sustainability measures impact the financial dynamics of major airports, and what factors contribute to the variations observed?

This chapter also outlines the objectives, including analysing the impact of sustainability measures on airport profitability, understanding the effect of national regulations, and identifying barriers to the adoption of sustainable practices. Additionally, the methodology is briefly introduced, and the organization of the dissertation is explained.

Chapter 2: Literature Review

This chapter presents a complete review of existing studies, focusing on key themes relevant to the research. Topics covered include:

- The historical development and characteristics of the aerotropolis model.
- The economic and environmental challenges faced by airports transitioning to sustainable practices.
- The effectiveness of various sustainability metrics and the implications of non-compliance in reporting standards.
- Financial versus environmental sustainability and their often-conflicting goals within airport operations.

The chapter critically evaluates gaps in the literature, such as the lack of detailed studies on how sustainability impacts financial performance in aerotropolises, setting the stage for this dissertation's contribution.

Chapter 3: Methodology and Data

The methodology chapter describes the analytical framework used to address the research question. It explains the selection of airports based on their alignment with the aerotropolis

model and their significance in global aviation. A detailed account of the Data Envelopment Analysis (DEA) methodology is provided, including:

- The rationale for choosing the CCR (output-oriented) model.
- The selection of input and output indicators, such as emissions, resource consumption, financial performance, and operational metrics.
- The data collection process, including the handling of gaps in sustainability data and the exclusion of abnormal years (2020 and 2021) due to the COVID-19 pandemic. The chapter concludes by introducing the Environmental and Financial Sustainability Impact on Aerotropolis Model (EFSI.OAM), developed to evaluate airport efficiency comprehensively.

Chapter 4: Presentation of Results and Discussion

This chapter is devoted to analysing the results obtained from the DEA. It presents the efficiency scores of selected airports across the analysed years and identifies patterns and deviations. Key discussions include:

- Consistently efficient airports and their best practices.
- Inefficient airports, their challenges, and the specific discrepancies in resource use and operational outcomes.
- Case studies of airports like Istanbul, Boston, and Guarulhos, highlighting their progress, setbacks, and areas for improvement. The chapter also explores the implications of national regulations, stakeholder priorities, and the costs of sustainability initiatives. It provides actionable insights for improving operational efficiency and balancing financial and environmental goals.
- Reviews research question and hypotheses.

Chapter 5: Conclusions

The concluding chapter synthesizes the key findings of the study, offering a critical evaluation of the objectives. Study limitations and possible future research are also approached.

2. LITERATURE REVIEW

2.1. INTRODUCTION

The importance of airports has grown a lot over time as the world has become more connected. Airports are now key places that support trade, tourism, and cultural exchange, which has led to a big increase in passenger numbers and goods being transported (Baker & Freestone, 2010). Cities with major airports have also benefited by growing economically and attracting businesses and jobs (Reiss, 2007).

Countries now see airports as more than just transport hubs. They are seen as important tools to grow regions quickly. This has led to interest in the aerotropolis model, where the areas around airports are developed with businesses, homes, and transport systems. These projects can turn airports into powerful drivers of growth for their surrounding areas (Reiss, 2007).

At the same time, there is more focus on sustainability. People are more aware of how greenhouse gas emissions harm the planet and cause climate change. The aviation industry is a major source of these emissions, and airports are under pressure to find greener ways to operate. As airports grow and adopt the aerotropolis model, it becomes more important to find a balance between expansion and caring for the environment (Sari et al., 2018). This means airports must work on creating solutions that help both the planet and the economy.

2.2. AEROTROPOLIS APPEARANCE

The idea of the aerotropolis has been discussed for nearly 20 years and is seen as an important part of urban and economic growth. Although there are two concepts that keep getting confused with each other which are aerotropolis and airport cities. Kasarda (2006) explained the difference between this two concepts. Airport cities focus on the area right next to the airport, while aerotropolises include a wider area with businesses, homes, and services connected to the airport. These can include things like shops, technology companies, logistics hubs, and even residential communities, showing how varied the businesses in an aerotropolis can be.

Shen and Cao (2016) studied how aerotropolises form and found two main ways this happens. The first way, called the endogenous gradient mode, happens when the airport grows and naturally attracts businesses that need air transport, like logistics companies, hotels, and factories. These businesses gather around the airport, helping the aerotropolis develop. The second way, called the exogenous mutant mode, happens when outside factors like government

policies or regional economic plans help the aerotropolis grow. In this case, big companies or government investments bring businesses to the area, which helps both the airport and the businesses grow together.

Charles et al. (2007) explained that aerotropolises can help regions grow economically by making them more attractive to businesses. But they also pointed out challenges, especially related to sustainability. One major issue is the heavy reliance on aviation fuel, which does not currently have a full replacement. This makes it crucial to include sustainability in aerotropolis planning. Without addressing environmental issues, aerotropolises might face problems in the long run, especially as climate concerns and stricter regulations become more common.

Aerotropolises provide significant potential for regional development by integrating economic activities around airports. However, the need for careful planning, particularly in addressing sustainability challenges, remains essential for their continued success. The literature reflects a balance between the opportunities and challenges associated with aerotropolis development, highlighting the importance of further research to address existing gaps in knowledge.

2.3. AEROTROPOLIS PLANNING AND ASSESSMENT TOOLS

Kasarda (2006) outlines the future planning of aerotropolises, expressing that "Aerotropolis optimization will require bringing together airport planning, urban planning, and business site planning in a synergistic manner so that development is economically efficient, aesthetically pleasing, and environmentally sustainable" (Kasarda, 2006, 12). This emphasises the critical importance of environmental sustainability in the planning of aerotropolises.

Later, Kasarda (2008) discusses the planning requirements of an aerotropolis, emphasising transportation, access, and the location of residential and commercial developments. Despite addressing the need for careful placement of these structures due to noise pollution and aircraft emissions, the author fails to emphasise the importance of solving these issues comprehensively by finding solutions to reduce both forms of pollution. Agarwal (2009, 17) also states that " (...) airport expansion and the development of new airports should include both the environmental costs and life-cycle costs.”. Although the literature introduces the topic of sustainability and the importance of planning future airports, it does not present implementable solutions which are crucial.

In China, Zhengzhou Airport is evolving into an aerotropolis, and in their plans for further development, their focus is on the "production of new energy batteries, on-board electronics, and intelligent driving devices," including Intelligent Connect Vehicles (ICV) and New Energy

Vehicles (NEV) (Kasarda, 2021). This illustrates that airport planning teams perceive sustainability as crucial for the effective functioning of an aerotropolis.

Dimitriou and Karagkouni (2022) developed an assessment tool for airport strategic plans. This tool is designed to evaluate and assist airports in making responsible choices when constructing elements such as roads and buildings. Its purpose is to ensure that the company grows in a manner that is beneficial for the environment and communities, a gap that can be found once again is the impact this can have in terms of costs.

Additionally, Banai (2016) study looks over the concept of the aerotropolis as a new urban development paradigm centred around airports highlighting the importance of sustainability in urban planning. "The challenge is to incorporate features of a sustainable urban form into the airport city district, which consists of structures with large footprints, such as industrial, manufacturing, warehousing, particularly in the existing land area surrounding airport terminal buildings." (Banai, 2026, 368), this passage shows the importance of investment in environmental measures in infrastructures in order to be able to create a sustainable aerotropolis but the author states that the creation of a regional city within an aerotropolis is crucial for sustainability.

2.4. AEROTROPOLIS CHARACTERISTICS

Aerotropolises have distinct characteristics, which were compiled by referencing various authors, such as:

1. Airport-Centric Business Hub: At the heart of an aerotropolis lies a major airport, around which there are a lot of aviation related businesses. This includes a dense cluster of cargo and logistics services, corporate parks, convention centres, retail outlets, hotels, and entertainment venues benefiting from their proximity to the airport (Flores-Fillol & Nicolini, 2006).
2. Spatial Organisation: there's a specific layout such as the airport serving as the central point, surrounded by industrial and commercial zones. These areas gradually transition into residential neighbourhoods and eventually rural expanses. This arrangement is designed to optimise land use and capitalise on the benefits of proximity to the airport (Flores-Fillol & Nicolini, 2006).

3. Economic Engine: Airports within aerotropolises serve as potent economic engines, attracting high-tech jobs and stimulating industrial expansion that demands rapid connectivity to global markets. (Menon, 2014).
4. Global Connectivity: Aerotropolises offer unparalleled connectivity not only locally or nationally but on a worldwide scale. They facilitate immediate and efficient connections for businesses, suppliers, customers, and partners, bolstering the flow of goods, services, and information across international borders (Menon, 2014).
5. Strategic Planning and Investment: Developing an aerotropolis demands meticulous planning and substantial investment as mentioned before, taking into consideration both financial resources and strategic planning. This involves detailed blueprints for the aerotropolis itself and investments in critical infrastructure such as roads, utilities, and telecommunications to support anticipated growth and development around the airport (Menon, 2014).
6. Innovative Technology Integration: Leading aerotropolises leverage smart technology and innovative infrastructure to boost operational efficiency, sustainability, and service excellence. This includes advanced transportation systems, digital connectivity, and eco-friendly technologies, positioning the aerotropolis as a modern and forward-thinking urban development (Kasarda & Chen, 2021).
7. Model of Airport-Centric Development: Aerotropolises exemplify how airports can transcend their traditional roles as transport hubs to become integral to urban development and economic strategy. This involves integrating the airport with the surrounding urban landscape and instigating its potential to drive economic vitality and urban rejuvenation (Kasarda & Chen, 2021).

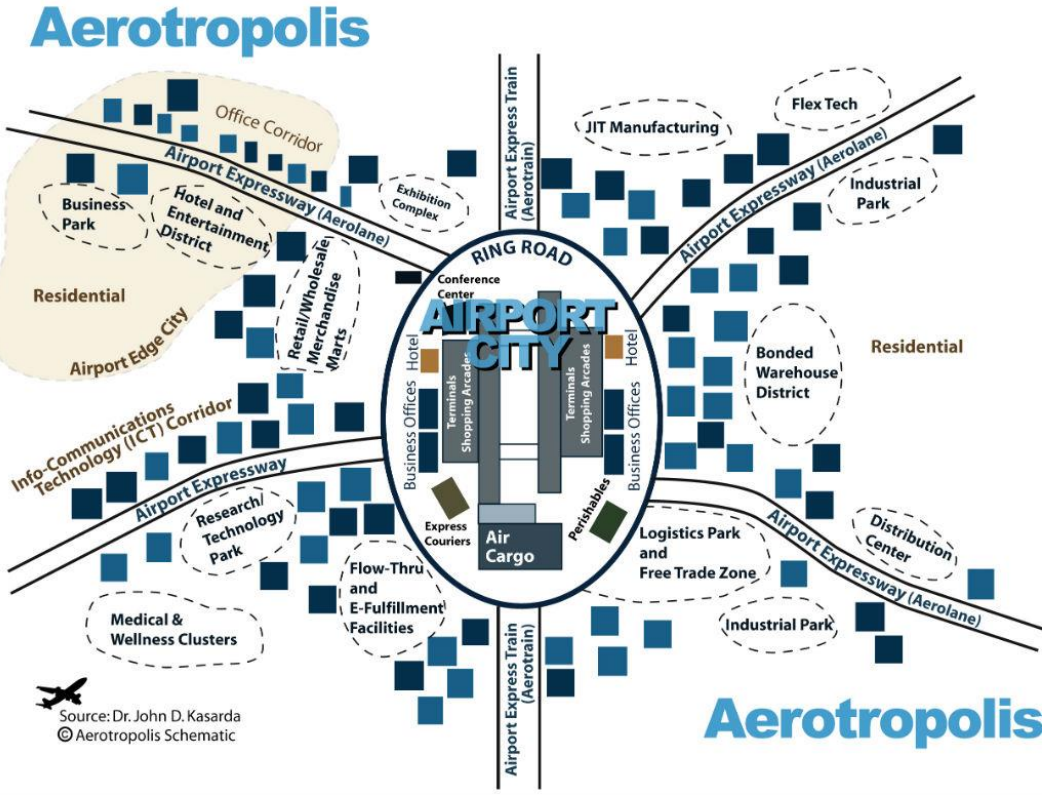

Figure 1: Aerotropolis Example

Source: Times of San Diego.

2.5. SUSTAINABILITY WITHIN SERVICE QUALITY

Wang et al. (2013) established criteria for ensuring service quality in an aerotropolis, with a particular emphasis on its role as a transfer hub. Although sustainability was not directly addressed in their paper, the emphasis on the aerotropolis's role as a transfer hub can impact its environmental footprint by potentially reducing the distance travelled by passengers. Moreover, the significance of government policy planning, highlighted in their findings, is crucial for environmental measures, as airports are more likely to implement changes in response to regulatory requirements.

However, subsequent research by Kasarda and Canon (2016) primarily focused on logistical, economic, and infrastructural factors, without recognizing environmental sustainability as a critical factor. This indicates that environmental concerns may not be receiving the priority they deserve within airport planning and development.

With increasing environmental awareness among consumers and investors, there is a growing focus on the environmental sustainability of services. In response to this trend, Kilkis and Kilkis (2016) developed the Sustainable Airport Index, considering multiple factors to assess airport

sustainability. Their study found a low R2 value between the SRA Index and passenger traffic, suggesting that factors beyond passenger numbers, such as sustainable practices adoption, significantly influence outcomes. This highlights the importance of improving aspects such as waste management and energy consumption to enhance overall sustainability efforts within airports and service quality.

2.6. SUSTAINABILITY REPORTS OMISSIONS/ NON-EXISTENCE

Research on airport sustainability reports reveals that many reports utilize the Global Reporting Initiative (GRI) framework, which is a widely accepted standard for sustainability reporting. However, a significant issue is the omission of certain critical indicators, such as stormwater quality and hazardous waste weight, as noted by Koç and Durmaz (2015). These omissions point to gaps in the comprehensiveness of reporting practices. The study suggests that combining financial and sustainability reports could improve the clarity and frequency of reporting. While this approach addresses the need for more integrated and frequent reports, it does not fully explore why specific indicators are omitted. Possible reasons for these omissions might include a lack of awareness about their importance or fears of reputational damage if unfavorable data is disclosed. Further investigation is needed to understand the motivations behind selective reporting and to develop solutions that encourage transparency.

Karagiannis et al. (2019) also explored the state of sustainability reporting and found that it remains relatively uncommon among airport operators. Even when sustainability reports are published, the level of detail is often limited, especially regarding specific metrics. Their study examines the need for airport management to prioritize comprehensive and accurate sustainability reporting. Improving the quality of these reports could help operators identify areas for improvement and align their practices with broader environmental goals. This highlights the role of well-informed managerial decisions in advancing sustainable operations.

Moreover, Karaman et al. (2018) discovered that about half of the companies in the aviation sector do not produce sustainability reports. This finding indicates that many companies are still far from fully integrating sustainability into their operational and strategic practices, despite growing awareness of its importance. The study discusses how boards of directors should actively promote sustainability by dedicating financial and human resources to this area. It also suggests the establishment of specialized sustainability committees or departments within organizations to focus on these issues and enhance reporting practices. Such organizational

changes are proposed to lead to more consistent and reliable reporting, helping airports better align with sustainability objectives.

The lack of widespread adoption of sustainability reporting raises broader questions about the barriers faced by airport operators. Some potential obstacles include limited resources, competing priorities, or a lack of regulatory pressure in certain regions. Addressing these challenges could involve a combination of incentives, industry standards, and possibly stricter regulations to encourage more airports to adopt transparent reporting practices.

Another factor contributing to gaps in sustainability reporting is the variability in how airports perceive and prioritize sustainability. Larger airports in regions with strict environmental regulations may be more likely to produce detailed reports, while smaller or less regulated airports might see sustainability as a lower priority. This disparity indicates a need for global frameworks that ensure all airports adhere to a consistent baseline for sustainability reporting.

Studies emphasize the importance of honest and detailed reporting not only for improving environmental performance but also for building trust with stakeholders, including passengers, investors, and regulatory bodies. Transparent reporting can allow airports to share progress, address shortcomings, and set measurable goals. It also rises accountability, ensuring that sustainability remains integrated into their operations without overlooking key challenges.

2.7. EFFECTIVE SUSTAINABILITY METRICS

Greer et al. (2020) emphasize the importance of developing effective sustainability metrics and frameworks to ensure that critical environmental themes are not overlooked. These metrics help airports track their progress in achieving sustainability goals and provide a clear structure for improvement. The study also highlights successful practices that can yield immediate benefits, such as sourcing low-emission electricity and electrifying ground transportation and gate equipment. These initiatives represent practical steps that airports can adopt to reduce their environmental impact in the short term while setting the stage for longer-term strategies

Despite the rapid evolution of the aviation sector, Janic (2010) provides a foundational framework for assessing sustainability through a broad range of metrics. These include infrastructure, operations, economics, environment, social factors, and institutional performance, alongside practical measures such as congestion, delays, and waste management. The study found that many of these indicators, particularly infrastructure, operational efficiency, and environmental practices, have shown gradual improvement over time. In some

cases, waste management has also advanced, with airports adopting strategies to minimize and recycle waste, thus reducing their environmental footprint.

Hubbard and Hubbard (2019) offer a different perspective, focusing on the role of sustainability metrics in infrastructure development. They argue that incorporating sustainability metrics during the planning phase of new projects is more effective than attempting to retrofit sustainable practices after construction. This approach is particularly relevant in rapidly growing regions like China and India, where large-scale infrastructure is being built to support expanding economies. Similarly, in countries like the United States, where aging infrastructure often needs significant upgrades, incorporating sustainability metrics early in the process can lead to more efficient and environmentally friendly outcomes (Hubbard and Hubbard, 2019). Their study underscores that forward-thinking planning not only reduces environmental impacts but also minimizes long-term operational costs.

Another critical aspect of effective sustainability metrics is their ability to provide airports with actionable insights (Greer et al., 2020). Metrics related to energy consumption, emissions, and waste generation (Raimundo et al., 2023) allow airports to identify specific areas that require improvement. For example, measuring direct and indirect greenhouse gas emissions can help airports target high-impact areas such as aircraft movements and ground operations. Similarly, tracking water usage and waste production enables airports to implement conservation and recycling programs that align with sustainability goals.

Furthermore, the implementation of sustainability metrics often varies based on regional and economic factors (Durrani & Forbes, 2004). Airports in developed regions with stricter environmental regulations and greater access to resources are more likely to adopt comprehensive metrics and frameworks (Greer et al., 2020). In contrast, airports in less developed regions may face challenges such as limited funding and technical expertise, which can hinder the adoption of effective sustainability measures (Greer et al., 2020). Addressing these disparities will require tailored approaches that consider the unique challenges and capacities of each airport.

Effective sustainability metrics not only track environmental impacts but also contribute to broader institutional goals (Rauch & Newman, 2009). For example, by aligning with global standards such as the United Nations Sustainable Development Goals (SDGs), airports can enhance their reputation and attract environmentally conscious stakeholders. Metrics that tie sustainability performance to financial outcomes can also incentivize management to prioritize

green initiatives, demonstrating that environmental responsibility and economic performance are not mutually exclusive.

Overall, the development and application of sustainability metrics are essential for ensuring that airports remain accountable and proactive in reducing their environmental footprint. These metrics serve as tools for measuring progress, identifying gaps, and implementing targeted strategies that balance operational efficiency with environmental stewardship.

2.8. FAILURE OF SUSTAINABILITY GOALS

Prather (2016) conducted research that found that 63% of the airports studied "(...) have adopted at least one sustainable initiative." (p.36). However, the remaining airports highlighted significant barriers to implementing sustainable measures, with the primary issues being high costs and a lack of funding. Smaller airports, in particular, often perceive their environmental impact as minimal, which discourages them from pursuing sustainability initiatives. This perspective suggests not only a lack of awareness about the potential environmental benefits but also a broader issue of insufficient information and education on the subject. The financial challenges associated with adopting sustainable measures also play a critical role, as many airports struggle to justify the upfront costs without immediate returns.

Vaio and Varriale (2020) provide further insight into the challenges airports face in meeting sustainability goals, focusing specifically on adherence to the United Nations Sustainable Development Goals (SDGs). Their study examined airports in Italy and found inconsistencies in meeting certain goals, particularly SDG 11 (Sustainable Cities and Communities) and SDG 17 (Partnerships for the Goals). While these goals were acknowledged in sustainability reports, actual implementation was often incomplete. The study points to financial constraints and operational priorities as common reasons for these shortfalls. It also highlights the importance of creating more supportive frameworks that enable airports to meet these goals effectively.

Another perspective comes from Banai (2016), who stresses the importance of integrating sustainable features into aerotropolis planning. Compact urban forms, which encourage walkability and the use of public transit, are vital for reducing emissions in areas that otherwise face increased environmental pressures due to high activity levels. However, Banai notes that implementing such features requires careful planning and significant investment, which may deter some airport operators. The challenges are particularly pronounced in regions with limited regulatory oversight or where economic pressures prioritize short-term gains over long-term sustainability.

Additional studies reveal that the lack of a unified global standard for sustainability practices contributes to the inconsistent adoption of green initiatives (Rogers et al., 2008). While some regions enforce stringent regulations and offer incentives, others provide little guidance or support, leaving airports to navigate sustainability efforts independently. This uneven playing field often results in varying levels of commitment and success across airports globally (Jia et al., 2024).

The reluctance of smaller airports to engage in sustainability initiatives also underscores the need for tailored approaches. For example, regional airports might benefit from scalable, cost-effective solutions that address their specific needs without requiring the same level of investment as larger hubs. Providing access to financial assistance, technical expertise, and shared resources could encourage broader participation in sustainability programs (Martin-Nagle & Klauber, 2015).

Moreover, the operational focus of many airports on maximizing efficiency and profitability can overshadow environmental priorities. While larger airports may have dedicated departments for sustainability, smaller ones often lack the resources or personnel to develop and implement comprehensive green strategies (Martin-Nagle & Klauber, 2015). Bridging this gap involves not only financial incentives but also greater awareness of the long-term benefits of sustainability, such as improved reputation, stakeholder trust, and compliance with future regulations.

These challenges illustrate the complex landscape of implementing sustainability goals in the aviation sector. The studies discussed point to a range of financial, operational, and structural factors that influence how airports approach sustainability, particularly in different regional and economic contexts.

2.9. FINANCIAL SUSTAINABILITY V ENVIRONMENTAL SUSTAINABILITY

Some studies have explored whether environmental sustainability aligns with financial sustainability in the aviation field. Forsyth (2011) concluded that this alignment is possible if effective measures are implemented. The study indicates that, in the short term, these solutions might not appear financially sustainable due to high initial costs, but they could become viable in the long term if their benefits outweigh the expenses. This raises questions about which measures are truly effective, whether they are applicable across the diverse aviation industry, and how they could be adapted to aerotropolises, which require even more comprehensive sustainability strategies.

Another study by Mańkowska et al. (2023) highlights barriers faced by airports in pursuing sustainability measures. The study categorizes airports by their level of commitment to sustainability, stating: "For airports with a high level of commitment, the most important barrier was the cost. In the case of airports with a medium level of commitment, the most significant barriers were unawareness of the potential benefits and a low priority assigned to green practices in the airport's strategic goals." These findings illustrate that even highly committed airports face financial constraints, while medium-commitment airports struggle with both informational and strategic challenges. Similar challenges are likely to arise in aerotropolises, which often demand more extensive measures. This demonstrates the need for targeted research on how sustainability efforts can be adapted and effectively implemented in these complex environments.

Raimundo et al. (2023) also address the need for future research to connect environmental impacts with economic outcomes for various airport stakeholders. This highlights a gap in current knowledge, where contradictions and insufficient data make it difficult to determine the true financial viability of sustainability measures. Such research could provide the evidence needed to encourage broader adoption of environmentally friendly practices by demonstrating clear economic benefits.

Budd et al. (2015) examined how UK airports responded to the challenge of adopting sustainable practices. The study found that while some strategies, such as energy efficiency measures and waste reduction programs, provide immediate benefits, financial constraints remain a significant hurdle. The study emphasizes the importance of policy guidance to ensure that economic and environmental goals are aligned. Budd et al. also point out that airports in developed countries have made substantial progress in implementing sustainable practices, serving as valuable examples for airports in developing regions. These findings suggest that knowledge sharing and collaboration between markets could help bridge gaps in sustainability practices globally.

Moreover, the implementation of sustainability measures often requires cooperation between multiple stakeholders, including airport operators, airlines, regulatory bodies, and local communities (Amaeshi & Crane, 2005). This complexity adds another layer of difficulty, as aligning the interests of diverse parties can be challenging. Airports in developing regions may also face additional barriers, such as limited access to funding or lack of technical expertise, which could delay or prevent the adoption of green practices (Martin-Nagle & Klauber, 2015).

Studies also point to the role of government incentives and regulations in overcoming financial barriers. Policies that offer tax benefits, grants, or subsidies for implementing green technologies can encourage airports to invest in sustainability (Shan & Ji, 2024). Such measures can reduce the initial financial burden and make long-term environmental benefits more attainable. Additionally, regulatory frameworks that require sustainability reporting and adherence to environmental standards can drive consistent progress in the industry.

Lastly, there is a growing recognition of the role that passengers and consumers can play in supporting sustainability efforts. Increased awareness and demand for environmentally friendly practices can pressure airports to prioritize green initiatives, even when financial constraints exist (Korba et al., 2023). This trend underscores the importance of public engagement and education in advancing both financial and environmental sustainability goals.

2.10. CONCLUSION

In conclusion, the evolution of airports into aerotropolises reflects the increasing significance of air travel in our globalised world. As cities with major airports continue to develop, the concept of aerotropolises emerges as a promising model for rapid and focused urban growth in some cases. However, alongside this growth comes a growing concern for sustainability, driven by the recent awareness of environmental issues such as greenhouse gas emissions and climate change.

While aerotropolises offer substantial economic benefits, they also present challenges, particularly in terms of ensuring long-term sustainability. The incorporation of environmental sustainability into aerotropolis planning is crucial for mitigating the environmental impact of increased air travel and urban development.

Efforts to integrate sustainability into aerotropolis planning are underway, with initiatives ranging from the adoption of new energy technologies to the development of assessment tools for evaluating airport strategic plans. However, there remain gaps in implementing comprehensive sustainability measures, including challenges in reporting practices and financial constraints.

In essence, the development of aerotropolises presents an opportunity to rethink the relationship between airports, urban development, and sustainability. By addressing the challenges and embracing the opportunities presented by aerotropolises, we can create thriving urban environments that are economically vibrant, socially inclusive, and environmentally sustainable for generations to come.

3. METHODOLOGY AND DATA

3.1. INTRODUCTION

The study aims to explore what are the financial implications of establishing sustainability measures in an airport in order to understand how aerotropolis should develop their sustainability plans in the future.

The literature review available focuses mainly on metrics of sustainability not referring to what affects the measures implementation such as the cost. In specific when it comes to aerotropolis planning sustainability tends to be mentioned as an important topic but it is never discussed how it should be implemented. The studies done on financial vs environmental sustainability are contradictory, even though most mentioned the implementation of these measures have a high cost some state that in the long term there might be a return in the investment.

3.2. STARTING QUESTION AND HYPOTHESES

This study has the starting question for the research:

How do sustainability measures impact the financial dynamics of major airports, and what factors contribute to the variations observed?

The hypotheses that emerge in this study are:

H1 - The implementation of sustainability measures at major airports positively correlates with increased operational costs.

H2 - The recognition of sustainability as a strategic priority influences the financial commitment of airports to environmental measures.

H3 - The regulation in the country on sustainability positively correlates with an increase of sustainability measures.

H4 - The absence of sustainability measures will negatively impact airport business.

3.3. RESEARCH METHODOLOGY

This study adopts a quantitative approach as it is the most effective method for gaining comprehensive insights into the relationship between sustainability measures and airport financial performance. To complement this, a qualitative SWOT analysis is integrated, providing a deeper understanding of the internal and external factors influencing airport performance. Together, these methods ensure a well-rounded analysis that combines numerical exactness with strategic interpretation.

The quantitative component of this research employs Data Envelopment Analysis (DEA), a well-established method for evaluating the efficiency of airports in balancing resource utilization and operational outcomes (Ferreira et al., 2015). DEA allows for comparisons across different airports, identifying those that operate efficiently and those that have room for improvement. This method will use a CCR (Constant Returns to Scale) model, which assumes that all DMUs operate at an optimal scale. By focusing on the proportional relationship between inputs and outputs, the CCR model provides a clear basis for measuring efficiency. The CCR model was chosen instead of the BCC model because the selected airports have similar passenger volumes, aircraft movements, and operational standards. This approach is particularly suitable for identifying performance targets and assessing whether inefficient airports are effectively utilizing their resources to maximize operational and financial outcomes. The results from the DEA will serve as a foundation for further analysis, enabling a deeper exploration of factors contributing to inefficiencies and potential strategies for improvement.

DEA is particularly suited for this research as it systematically assesses the effectiveness of airports in integrating sustainability measures into their operations while maintaining financial performance. The analysis will provide efficiency scores for each airport, highlighting patterns of high or low performance over the years studied. These results will serve as a foundation for identifying specific areas where airports can improve their practices to achieve better alignment between sustainability goals and operational outputs (Ferreira et al., 2015).

To complement the DEA analysis, a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis will be conducted for each inefficient airport identified. While DEA quantifies efficiency, the SWOT analysis provides a broader contextual understanding of the challenges and opportunities each airport faces. It will examine internal factors, such as operational

strategies and technological capabilities, alongside external elements, such as regulatory frameworks and market dynamics.

The purpose of integrating SWOT analysis is to provide insights that go beyond numerical efficiency scores. By understanding the strengths that need to be kept, the weaknesses that need addressing, and the external factors that influence airport operations, this study aims to propose tailored recommendations for each airport to enhance their overall performance.

The research involves a comprehensive data collection process to ensure a robust foundation for analysis. Data will be gathered from financial and sustainability reports, as well as from publicly available information, such as airport accreditation levels under the Airport Carbon Accreditation (ACA) program. This data will be collected from the websites mentioned in appendix 1. The dataset will cover a six-year period, from 2018 to 2023, excluding abnormal years such as 2020 and 2021, which were heavily affected by the COVID-19 pandemic.

To ensure consistency and accuracy, gaps in data will be addressed by cross referencing multiple sources or making informed estimates based on comparable airports. This will ensure that the analysis remains comprehensive and reliable, reflecting realistic operational conditions for the selected airports.

The integration of DEA and SWOT analysis provides a holistic approach to understanding airport efficiency. DEA identifies efficiency levels and highlights discrepancies in performance, while SWOT analysis contextualizes these findings by examining strategic and operational factors. This combination ensures that the results are not only diagnostic but also prescriptive, enabling the development of actionable strategies for improvement.

By using DEA as the primary evaluation tool and SWOT analysis as a complementary method, the study addresses both quantitative and qualitative dimensions of airport performance. This methodological collaboration is essential for achieving the research objectives and providing meaningful insights into how sustainability measures impact the financial and operational dynamics of major airports.

The rational to use of DEA and SWOT analysis together ensures that the research captures both the measurable and contextual aspects of airport performance. DEA provides a clear, data-driven basis for comparing airports, while SWOT analysis offers the flexibility to explore the broader implications of these results. This approach is particularly valuable for understanding

the complexities of integrating sustainability into airport operations and the unique challenges faced by each airport.

By employing these methods, the study aims to provide a comprehensive perspective on airport performance, identifying not only where inefficiencies lie but also how they can be addressed in a strategic and sustainable manner.

3.4. AEROTROPOLIS CHARACTERISTICS RESUMED

Before conducting a Data Envelopment Analysis, it is essential to establish the main characteristics of the aerotropolis so that the airports selected for this study can effectively contribute to the intended conclusions.

As mentioned in the literature review especially on the work done by John D. Kasarda, some of the characteristics of an aerotropolis are as follows:

1. There exists a business hub surrounding the airport
2. The airport serves as the central point of the aerotropolis in terms of geographic distribution
3. The airport functions as the economic engine of the region
4. It possesses global connectivity
5. It adheres to a strategic plan and receives investments accordingly
6. It incorporates innovative technology
7. It is seamlessly integrated with the urban landscape

Keeping in mind the features outlined, the airports that will be explored are defined in Table 1.

Table 1: Airports that will be studied.

Source: Author.

Location	Airports	IATA Code
Europe	Josep Tarradellas Barcelona–El Prat Airport	BCN
	Amsterdam Airport Schiphol	AMS
	Frankfurt am Main Airport	FRA

	İstanbul Havalimanı Airport	IST
Asia	Hong Kong International Airport	HKG
	Tokyo International Airport	HND
	Singapore Changi Airport	SIN
Oceania	Kingsford Smith International Airport	SYD
North America	Boston Logan International Airport	BOS
South America	Governador André Franco Montoro International Airport	GRU

3.5. DEA EXPLAINED

Data Envelopment Analysis (DEA) is a nonparametric methodology for evaluating the efficiency of decision-making units (DMUs) that convert multiple inputs into multiple outputs, as described by Bowlin (1998). This technique provides a robust framework for assessing performance, particularly in contexts where traditional efficiency measurement methods may fall short.

The two main models of DEA are the CCR model (Constant Returns to Scale) and the BCC model (Variable Returns to Scale). The CCR model, introduced in 1978, is named after its developers Charnes, Cooper, and Rhodes. It assumes that an increase in inputs leads to a proportional increase in outputs and is ideal when all DMUs are operating at an optimal scale (Banker et al., 1984). The CCR model uses the mathematical formulation shown in Figure 1, aiming to maximize efficiency while ensuring that no DMU exceeds an efficiency score of 1.

$$\max h_0 = \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}} \quad \text{subject to} \quad 1 \geq \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}}, \quad j = 1, \ldots, n, \quad \text{with} \quad (1)$$

$$u_r, v_i > 0,^1 \qquad i = 1, \ldots m; \quad r = 1, \ldots s.$$

Here the $y_{rj}, x_{ij} > 0$ represent output and input data for decision making unit (DMU) j

Figure 2: CCR Mathematical formulation.

Source: Banker et al.,1984.

The BCC model, introduced by Banker, Charnes, and Cooper in 1984, incorporates variable returns to scale, acknowledging that DMUs may operate under increasing, constant, or decreasing returns to scale. This model is particularly suitable for DMUs of varying sizes or scales of operation (Toloo & Nalchigar, 2008). The flexibility of the BCC model allows it to account for the diverse operational environments encountered in real-world applications.

Traditionally, DEA models have been classified as either input-oriented or output-oriented, focusing on input reduction or output expansion, respectively (Li Guang, 2001). The input-oriented model minimizes inputs while maintaining the current level of outputs, making it suitable for cost reduction or resource-constrained environments. In contrast, the output-oriented model maximizes outputs while keeping inputs constant, which is ideal for performance maximization or high-competition contexts.

By applying DEA to airport data, it is possible to identify which airports are most efficient in balancing sustainability practices with economic and operational performance. This analysis offers valuable insights for airport management and policy-making, enabling stakeholders to pinpoint areas for improvement and strategically allocate resources.

Incorporating sustainability into DEA models highlights the trade-offs and synergies between environmental initiatives and financial performance. Airports that successfully integrate sustainability measures into their operations can serve as benchmarks for others, promoting industry-wide advancements in both efficiency and environmental responsibility. Furthermore, understanding the role of national regulations and strategic priorities in shaping sustainability outcomes provides a comprehensive view of how external factors influence efficiency metrics.

3.6. DATA COLLECTION FOR THE DEA

3.6.1. INDICATORS

As mentioned before a Data Envelopment Analysis will be used so first the group of homogeneous decision-making units (DMUs) has to be established. Our DMUs are 10 airports mentioned on Table 1: Josep Tarradellas Barcelona–El Prat Airport, Amsterdam Airport Schiphol, Frankfurt am Main Airport, İstanbul Havalimanı Airport, Hong Kong International Airport, Tokyo International Airport, Singapore Changi Airport, Kingsford Smith International Airport, Boston Logan International Airport, and Governador André Franco Montoro International Airport.

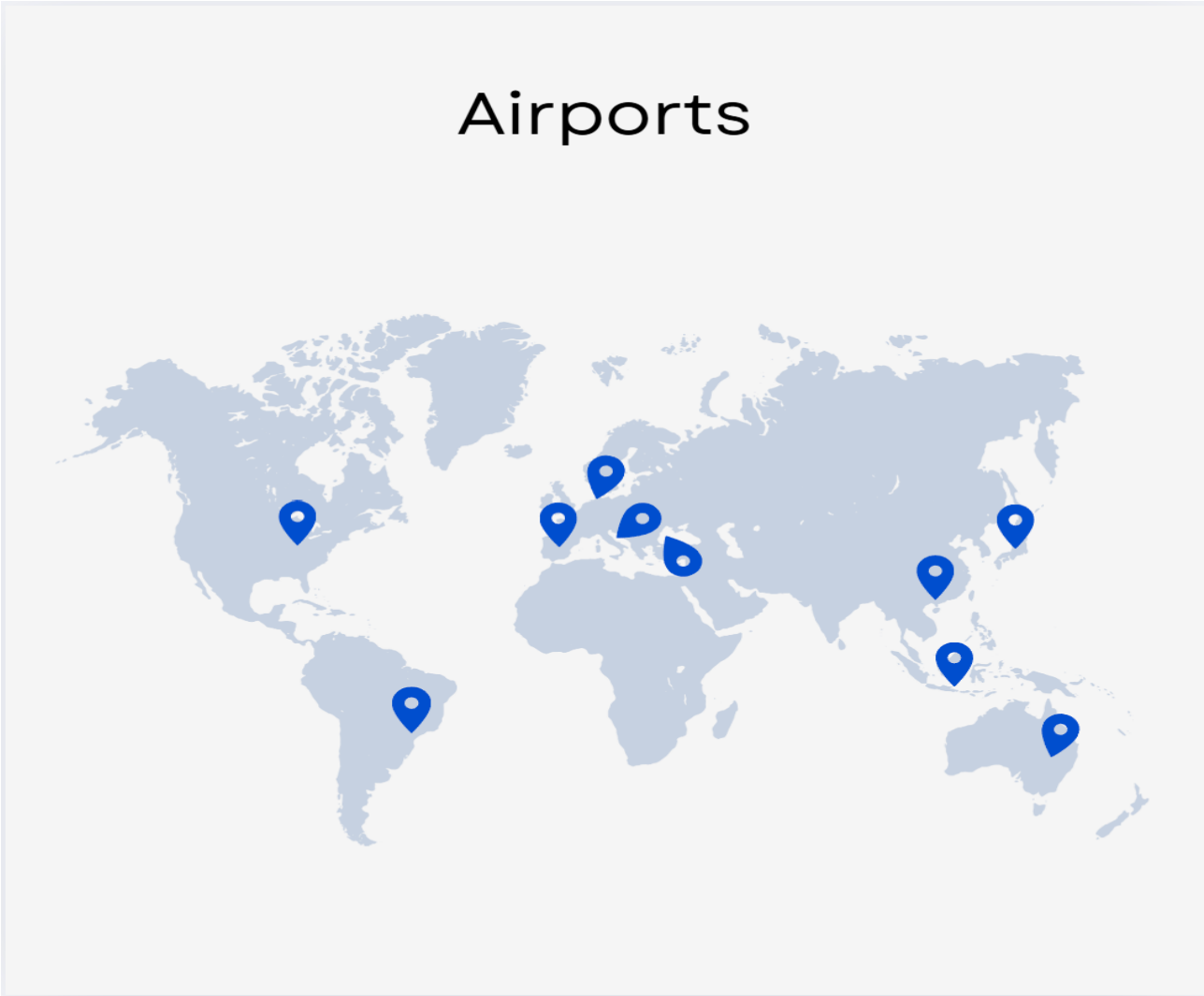

Figure 3: Airport to be study map.

Source: Author.

The performance indicators that were used are financial, operational and sustainability indicators to evaluate the effects that sustainability measures have on financial and operational indicators. The 8 performance indicators that will be used are:

5 Inputs: Direct Emissions, Total Electricity Consumption, Total Waste Generated, Water Consumption and Airport Carbon Accreditation level.

3 Outputs: EBITDA, Number of Passengers and Aircraft Movements.

The data for BCN, AMS, and FRA airports were available as part of a group company. For the first two, the percentage representation of each airport was calculated based on the proportion of passengers for that airport relative to the group. For FRA, the annual report stated that the

airport accounted for 58% of the group's results, and this percentage was used to calculate the data.

Due to the lack of information on sustainability measures, predictions and assumptions were made to avoid losing data for those airports. At AMS airport, data on total waste generated and water consumption were unavailable. To estimate these indicators, an average per million passengers was calculated using FRA airport data, as both airports have a similar number of passengers and are located in the European Union, subject to similar laws and measures.

For IST airport, EBITDA data was not available. To address this, FRA airport data was used due to a similar number of passengers and aircraft movements. EBITDA per million passengers was calculated for Frankfurt, enabling an estimate of EBITDA for IST. However, this is a significant fragility, as the management of the airports differs considerably.

Other data might have been collected from secondary sources and not from official airport reports to allow the evaluation of all airports.

For the calculation of EBITDA, which was originally collected in local currencies, the website WISE was used to convert the amounts to euros based on the exchange rates applicable at the time the financial reports were issued for each airport.

3.6.2. TIME FRAME

The time frame for this study spans from 2018 to 2023. However, the years 2020 and 2021 were excluded due to the impact of COVID-19, as the data from these years is disrupted and does not accurately reflect the reality of the airport industry. Istanbul Airport is also excluded from the analysis for 2018 since it only began operations in April 2019. For 2019, Istanbul Airport is included in the calculations as it was operational for the entire year, providing consistent and representative data for that period.

The decision to exclude 2020 and 2021 was based on the unprecedented global disruptions caused by the pandemic, which led to significant declines in air travel and operational changes at airports worldwide. Including data from these years could skew the results and compromise the validity of the analysis, particularly in evaluating long-term sustainability and financial trends.

Similarly, the exclusion of Istanbul Airport from the 2018 dataset ensures that the analysis remains focused on fully operational facilities with complete data for the year. By including

Istanbul Airport from 2019 onward, the study incorporates its contribution to the dataset without introducing inconsistencies.

This approach ensures that the dataset accurately represents the operational and financial dynamics of major airports, enabling robust analysis and meaningful conclusions about the impact of sustainability measures on airport performance over time.

3.6.3. CONSTRUCTED DATABASE

The database for the Data Envelopment Analysis (DEA) was designed to ensure consistency and comparability across the selected airports and years. It systematically organizes data for each airport, represented as a Decision-Making Unit (DMU), to facilitate the evaluation of efficiency levels based on sustainability and operational performance.

The database is structured as shown in the table below. Each row represents an airport (DMU) and includes data on its location, specific inputs, and outputs for the respective years under analysis. The columns reflect the various variables included in the study, ensuring all relevant indicators are accounted for and aligned with the requirements of the DEA model.

Table 2:Inefficient Airports Target Inputs

Source: Author.

Location of the airport	DMUs	Input 1	Input 2	(...)	Input n	Output 1	Output 2	(...)	Output n
Location 1	Airport 1								
Location 2	Airport 2								
(...)	(...)								
Location n	Airport n								

3.7. SWOT ANALYSIS EXPLAINED

SWOT analysis, Figures 5, is a strategic planning framework used to evaluate the Strengths, Weaknesses, Opportunities, and Threats associated with a specific organization or project. This

tool provides a structured approach to understanding both internal capabilities and external factors that influence performance.

The four things to be analysed are:

- Strengths: Internal factors that provide a competitive advantage or enhance performance. For airports, strengths might include advanced infrastructure, strong financial performance, or established sustainability programs.
- Weaknesses: Internal limitations or areas where the organization underperforms. These could include outdated technologies, inefficient processes, or a lack of sustainability measures that delay operational success.
- Opportunities: External factors or trends that the organization can use to improve its performance or to achieve goals. For airports, opportunities might arise from advancements in technology, favourable regulatory frameworks, or growing consumer demand for environmentally conscious practices.
- Threats: External challenges or risks that could negatively impact performance. Airports may face threats such as economic instability, increasing competition, stricter environmental regulations, or unforeseen disruptions like global pandemics.

In this research, SWOT analysis serves as a complementary qualitative tool to the quantitative Data Envelopment Analysis. While DEA identifies efficiency levels and areas requiring improvement, SWOT analysis provides a deeper contextual understanding of the factors contributing to each airport's performance. By examining the internal strengths and weaknesses alongside external opportunities and threats, this approach highlights the broader strategic and environmental dynamics affecting efficiency.

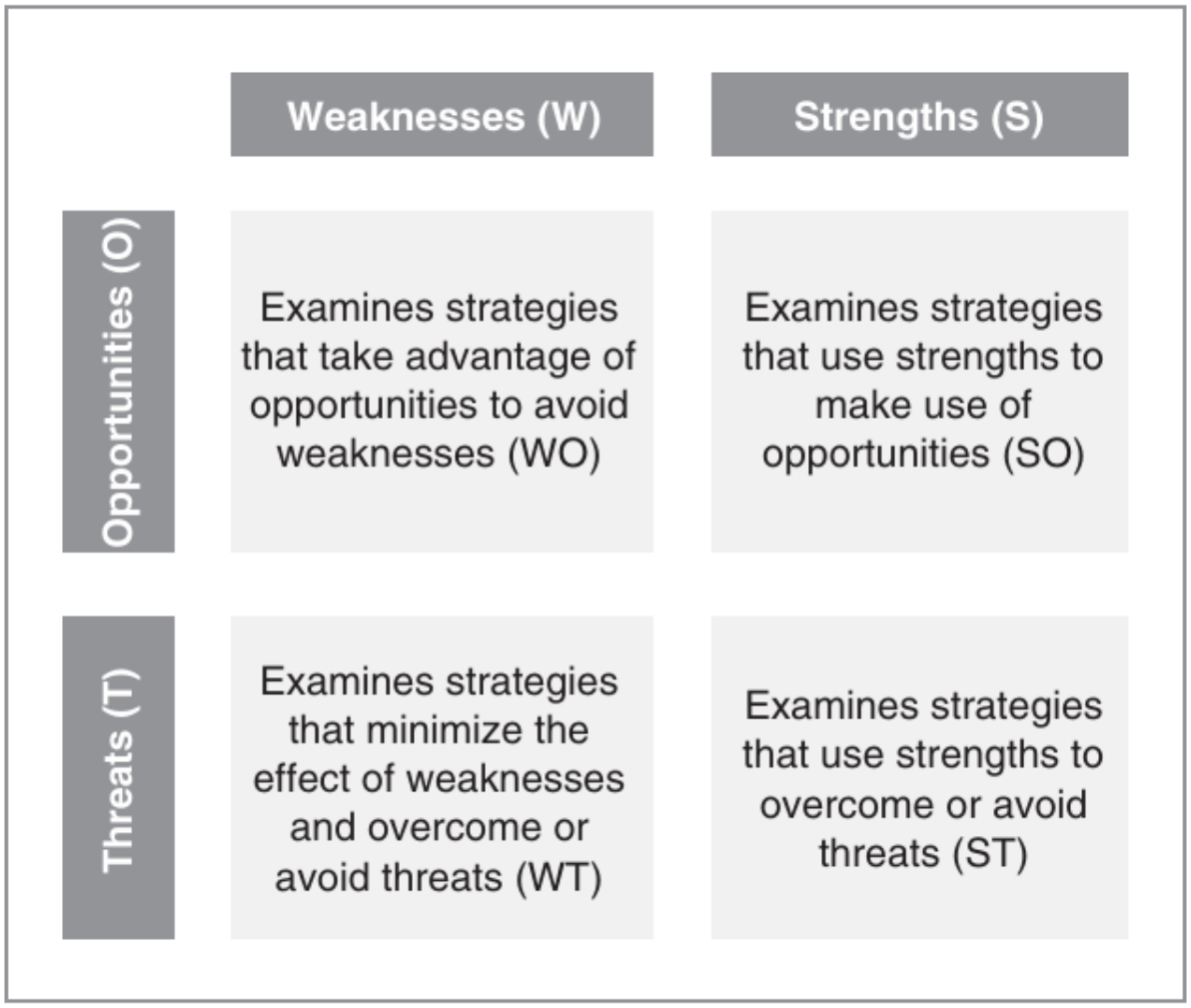

Figure 4: SWOT Analysis.

Source: Sammut-Bonnici & Galea (2015).

The SWOT analysis will be applied to the airports identified as inefficient through the DEA results and one efficient to compare. It will focus on:

- Internal Evaluation: Identifying the key strengths and weaknesses of each airport.
- External Context: Analysing opportunities and threats arising from regulatory environments, market trends, and external pressures such as competition or global crises.
- Strategic Recommendations: Using the insights gained from SWOT to propose actionable strategies tailored to each airport's unique circumstances. These recommendations aim to address inefficiencies, improve sustainability measures, and enhance overall operational and financial performance.

By combining SWOT analysis with DEA, this study ensures a comprehensive evaluation of airport efficiency and provides actionable insights to guide airports in aligning their operational goals with sustainability priorities.

3.8 MODEL - EFSI.OAM - ENVIRONMENTAL AND FINANCIAL SUSTAINABILITY IMPACT - ON AEROTROPOLIS MODEL

There are other studies that use the DEA model, such as Ferreira et al. (2015), although the model that will be constructed and developed in this thesis focuses on economic and green sustainability in aerotropolises, unlike any other. This model is important due to the development of major airports and their surroundings possibly becoming an aerotropolis, which can have a significant impact on emissions. Therefore, it is important to develop a model that takes into account operational, economic, and green sustainability.

To create this method, the first step is to define the type of analysis to be used, which in this case will be Data Envelopment Analysis (DEA). This decision aligns with the need to assess the efficiency of Decision-Making Units (DMUs) in achieving environmental and financial sustainability within the Aerotropolis context.

Step 1: Define the Analysis Framework

- **Define Analysis Type:** DEA.
- **Objective:** Measure efficiency in integrating environmental, financial and operational efforts.

Step 2: Define DMUs and Indicators

- **DMUs:** Airports operating close to the Aerotropolis model.
- **Indicators:**
    - **Input Indicators:**
        - Resource consumption (e.g., energy usage, water usage).
        - Environmental impact metrics (e.g., CO2 emissions, waste reduction).
        - Investments in sustainability initiatives.
    - **Output Indicators:**
        - Operational metrics (e.g., aircraft movements)
        - Financial performance metrics (e.g., revenue, profit margins).

- Passenger satisfaction related to sustainability measures.

Step 3: Data Collection and Preparation

- Gather relevant data for the selected indicators.
- Ensure data quality and consistency for comparison across DMUs.
- Normalize data to standardize different measurement units.

Step 4: Determine DEA Model

- **Model Type:** CRS (Constant Returns to Scale) output-oriented model.
- **Rationale:**
  - Focus on maximizing outputs given the input levels.
  - Suitable for evaluating performance in scenarios where scaling efficiency is critical.

Step 5: Data Processing

- Utilize specialized software (onlineoutput) to analyze data for each year.
- Generate efficiency scores and rank DMUs based on their environmental and financial sustainability impact.

Step 6: Results Presentation

- Develop efficiency rankings for DMUs.
- Compare performance across years to identify trends.
- Highlight top-performing airports and areas for improvement in lower-performing airports.
- Do SWOT analysis for each inefficient airport.

Step 7: Discussion and Final Considerations

- Analyze findings to draw insights into:
  - Key factors driving efficiency.
  - Challenges faced by less efficient DMUs.
  - Recommendations for policy and operational improvements.

- Discuss implications for the Aerotropolis model.
- Summarize contributions to environmental and financial sustainability in aviation.

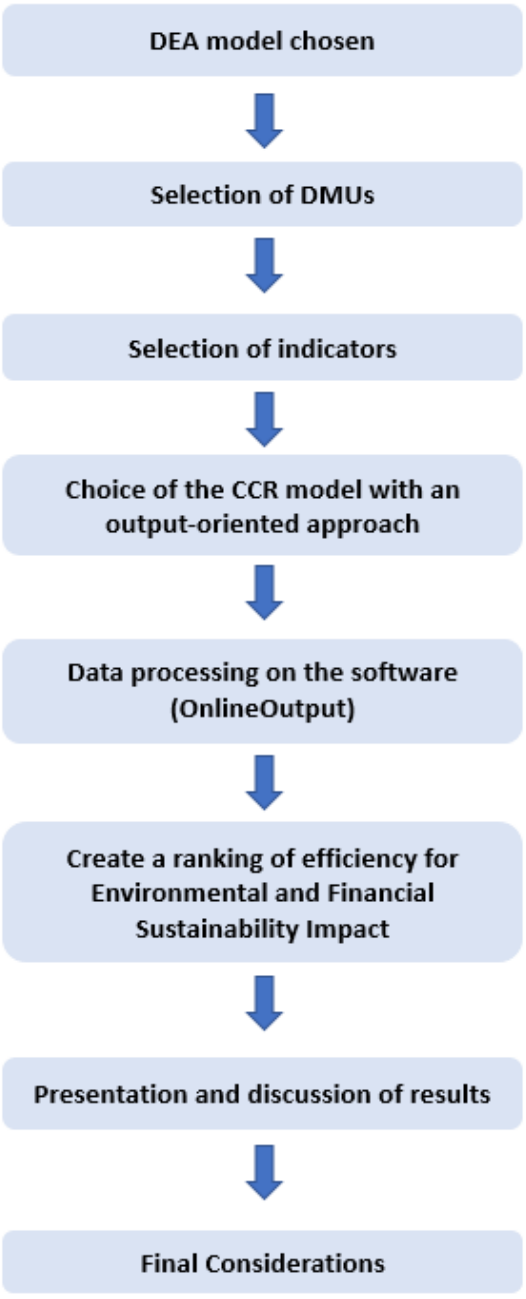

Figure 5: EFSI.OAM model construction process.

Source: Author.

This structured approach, Figure 6, ensures that the EFSI.OAM model comprehensively evaluates the dual impact of environmental and financial sustainability within the Aerotropolis framework, providing actionable insights for stakeholders.

4. PRESENTATION OF RESULTS AND DISCUSSION

4.1. AIRPORT RANKINGS

In this model, 10 airports around the globe were studied using sustainability, operational, and financial indicators to evaluate the efficiency of airport operations in utilizing sustainability measures (inputs) to achieve desirable financial and operational outcomes (outputs). Istanbul Airport was not considered in the 2018 evaluation since it only opened in April 2019. However, for 2019, it was included by estimating the numbers as if it had been operating for the full year.

In Table 2, the ranking of efficiency for each airport during the analysed years is presented.

Table 3: Airport Efficiency ranking.

Source: Author.

Airport (IATA Codes)	2018	2019	2022	2023
BCN	1	1	1	1
AMS	0.973	1	0.943	1
IST	-	0.776	0.827	0.979
SIN	1	1	1	1
FRA	1	1	1	1
HND	1	1	1	1
SYD	1	1	1	1
BOS	0.982	0.998	1	0.873
HKG	1	1	1	1
GRU	0.701	0.674	0.368	0.429

**The airport is considered inefficient, in case the efficiency is less than 1.*

BCN, SIN, FRA, HND, SYD and HKG are airports that show a consistent efficiency score of 1 across all years (2018, 2019, 2022, and 2023). This implies that these airports are operating at the efficiency frontier, fully utilizing their inputs to achieve the desired outputs. They likely have strong sustainability measures, which could contribute to better financial and operational outcomes.

Istanbul Airport shows efficiency improvements from 0.776 in 2019 to 0.827 in 2022 and reached 0.979 in 2023. This suggests a significant improvement in the airport's sustainability practices or operational outcomes, nearing optimal efficiency by 2023.

On the other hand, Amsterdam Airport's efficiency started at 0.973 in 2018, reached 1 in 2019, then declined to 0.943 in 2022 but regained full efficiency in 2023. This indicates efforts to address prior challenges and achieve consistent sustainability and operational balance.

Boston Airport's efficiency has also been unstable, as it nearly reached full efficiency with 0.982 in 2018 and 0.998 in 2019, achieved full efficiency in 2022, but then dropped to 0.873 in 2023, signalling a potential decrease in sustainability measures or financial performance.

Guarulhos Airport shows a significant decline over time, from 0.701 in 2018 to 0.674 in 2019, 0.368 in 2022, and 0.429 in 2023. This persistent inefficiency suggests substantial issues, possibly tied to limited sustainability implementation or financial pressures.

4.2. INDICATORS EVALUATION TO GET TO EFFICIENCY

This method enabled the identification of the target inputs and outputs required to enhance performance and achieve optimal efficiency levels. As demonstrated in Table 2, four airports were identified as inefficient during the years studied: Schiphol Airport (AMS), Istanbul Airport (IST), Boston Airport (BOS), and Guarulhos Airport (GRU). Unlike other airports, which consistently operated on the efficiency frontier with no adjustments necessary, these inefficient airports displayed significant deviations in both inputs and outputs.

These inefficiencies highlight opportunities for improvement, in areas such as emissions, energy consumption, waste management and water consumption, which could be reduced to align with more sustainable practices. Simultaneously, outputs such as EBITDA, number of passengers, and aircraft movements could be increased to better align with the efficiency frontier. Addressing these discrepancies would allow the airports to improve their sustainability and operational performance.

Tables 3 and 4 will further illustrate these discrepancies, listing the specific differences in inputs and outputs for these airports. This analysis can guide strategic decisions and the development of targeted measures to achieve alignment with the efficiency frontier.

4.2.1. TARGET INPUTS

For inputs, the data used was sustainability data, as that is what needs to be minimized. The ones used were:

- Direct Emissions (tCO_2e): Total greenhouse gas emissions directly generated by airport operations (scope 1). It reflects the environmental impact of airport activities. Lower emissions typically indicate better sustainability practices, such as energy efficiency or the use of renewable energy sources.
- Total Electricity Consumption (kWh): Total electricity consumed by the airport for its operations. High consumption may indicate energy inefficiency, while lower consumption suggests the adoption of energy-saving technologies or practices, contributing to sustainability goals.
- Total Waste Generated (metric tons): Total amount of waste generated by the airport, including operational and passenger-related activities. Waste generation impacts an airport's environmental footprint. Effective waste management, such as recycling programs, can reduce this value and improve sustainability.
- Water Consumption (m^3): Total water usage in airport operations. High water consumption can strain local resources and sustainability efforts. Efficient water management, such as recycling and conservation, is crucial for minimizing environmental impact.

In Table 4, the target inputs for inefficient airports are presented over the years analysed.

Table 4: Inefficient Airports Target Inputs.

Source: Author.

Airports	Inputs	2018	2019	2022	2023
AMS	Direct Emissions (tCO2e)	20339 → 9537	19037 → 19037	11616→ 11616	9828 → 9828
	Total Electricity Consumption (kWh)	200000000 → 200000000	198000000 → 198000000	194040000 → 194040000	188218800 → 188218800

Airports	Inputs	2018	2019	2022	2023
	Total Waste Generated (metric tons)	16621→ 10655	16612 → 16612	11366→ 8213	17295 → 17295
	Water Consumption (m^3)	1289384 → 998862	1549324 → 1549324	1574421 → 1574421	1335223 → 1335223
IST	Direct Emissions (tCO2e)	N/A	49828 → 19769	21799 → 16764	19611 → 13425.79
	Total Electricity Consumption (kWh)	N/A	238664496 → 238664496	234167578 → 222779718	232798953 → 232798953
	Total Waste Generated (metric tons)	N/A	35636→ 17183	43507 → 9900	53135 → 14761.79
	Water Consumption (m^3)	N/A	1775564 → 1647260	1330820 → 1330820	1492193 → 1367012.28
BOS	Direct Emissions (tCO2e)	47493 → 6793	51359 → 7750	31415 → 31415	30001.33 → 7250.04
	Total Electricity Consumption (kWh)	151682956 → 151682956	169634586 → 169634586	250484024 → 250484024	282200989 → 275480066
	Total Waste Generated (metric tons)	10614 → 7916	10734 → 8916	12840 → 12840	13114 → 13114
	Water Consumption (m^3)	885195 → 753750	915505 → 915505	627256 → 627256	768663 → 768663
GRU	Direct Emissions (tCO2e)	22572 → 8142	22643 → 9745	28270→ 20501	28359 → 17011
	Total Electricity Consumption (kWh)	162151000 → 162151000	174088000 → 174088000	277868130 → 277868130	297318899 → 295276638
	Total Waste Generated (metric tons)	11346 → 8792	11016 → 9803	14244 → 12426	13817 → 13817

Airports	Inputs	2018	2019	2022	2023
	Water Consumption (m^3)	1038055→ 813381	1037971 → 1037971	1801957 → 1684456	1801813→ 1506932

*All numbers were approximated to the nearest unit since it is sustainability values.

4.2.2. TARGET OUTPUTS

For outputs, the data used was operational and financial data, as well as Airport Accreditation Level, since that is what needs to be maximized. The ones used were:

- EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization) (M): A measure of the airport's profitability and financial performance. Higher EBITDA indicates better financial management and operational efficiency, suggesting that the airport is profitable while maintaining sustainability measures.
- Number of Passengers (M): Total number of passengers served by the airport in a given year. Passenger volume is a key indicator of an airport's operational scale and success. A higher number suggests strong demand and operational efficiency, provided it doesn't come at the cost of sustainability. It helps indicate that airports with a similar number of passengers but very different sustainability measures may not be as efficient in terms of sustainability.
- Aircraft Movements (K): Total number of takeoffs and landings at the airport. Reflects the airport's capacity to handle air traffic. Higher movements demonstrate operational capability but must be balanced with sustainability efforts, such as emission control.
- ACA Level (Airport Carbon Accreditation Level): An accreditation level awarded to airports based on their carbon management efforts (e.g., mapping, reduction, optimization, neutrality). A higher ACA level indicates strong commitment to sustainability and environmental responsibility, aligning with the airport's strategic goals to reduce carbon emissions.

In Table 5, the target outputs for inefficient airports are presented over the years analysed.

Table 5: Guarulhos Airport Target Outputs.

Source: Author.

Airports	Inputs	2018	2019	2022	2023
AMS	EBITDA (M)	552.45 → 1232.06	599.43 → 599.43	155.73 → 829.33	304.50 → 1395.12
	Nº PAXs (M)	70.96 → 72.96	71.68 → 71.68	52.47 → 55.62	61.89 → 84.10
	Aircrafts Movement (K)	517.73 → 532.31	515.81 → 515.81	422.30 → 447.62	464.72 → 626.76
	ACA Level	3.5 → 4.60	3.50 → 3.50	3.50 → 5.27	4.50 → 6.17
IST	EBITDA (M)	N/A	684.01 → 881.53	783.54 → 947.25	894.40 → 894.40
	Nº PAXs (M)	N/A	70.56 → 90.94	64.28 → 77.71	76.03 → 76.03
	Aircrafts Movement (K)	N/A	433.33 → 558.46	329.90 → 501.47	505.97 → 505.97
	ACA Level	N/A	0 → 4.13	1 → 5.80	3 → 3
BOS	EBITDA (M)	341.06 → 963.01	380.64 → 956.116	429.18 → 429.18	475.30 → 1054.30
	Nº PAXs (M)	39.50 → 54.16	41.90 → 58.87	31.10 → 31.10	39.20 → 61.73
	Aircrafts Movement (K)	412.16 → 419.82	426.51 → 427.17	341.98 → 341.98	396.54 → 454.07
	ACA Level	0 → 3.66	0 → 3.94	0 → 0	1 → 5.07
GRU	EBITDA (M)	297.12 → 972.21	307.25 → 910.59	397.48 → 1242.69	397.88 → 1603.98
	Nº PAXs (M)	42.23 → 60.25	43 → 63.83	34.50 → 93.76	41.30→ 96.19
	Aircrafts Movement (K)	291.99 → 416.55	293.92 → 436.29	242.90 → 660.12	274.92 → 640.29
	ACA Level	0 → 3.56	0 → 3.85	0 → 7.71	0 → 6.28

*All numbers were approximated to the nearest 2 decimal places since the numbers are in M and K.

4.3. RESULTS DISCUSSION

4.3.1. EFFICIENCY PATTERNS ACROSS AIRPORTS

The analysis reveals that while several airports maintain consistently high efficiency scores, others struggle to optimize their operations fully. These inefficient airports display varying degrees of challenges in aligning resource inputs with operational outputs, often reflecting structural, operational, or strategic deficiencies. Key factors contributing to inefficiency include outdated infrastructure, limited adoption of technological advancements, suboptimal workforce management, and insufficient integration of sustainability measures.

Lower efficiency scores among certain airports highlight clear areas for improvement. These include reducing resource consumption through effective energy management, optimizing operational performance by streamlining processes, and implementing sustainable practices such as renewable energy adoption, waste reduction programs, and carbon offset initiatives. Moreover, discrepancies in efficiency scores emphasize the critical role of robust strategic planning, stakeholder engagement, and regulatory compliance in driving operational improvements.

The findings indicate that regulatory frameworks significantly influence efficiency outcomes. Airports in regions with stringent sustainability regulations, such as those in the European Union, often achieve higher efficiency scores. This alignment underscores how proactive policies and incentives can drive operational and sustainability enhancements. Conversely, airports in regions with less developed sustainability policies face challenges in prioritizing and implementing green initiatives.

Financial constraints also emerged as a notable barrier, particularly for airports attempting to balance upfront investments in sustainability with operational profitability. Airports like Amsterdam and Istanbul, which have undertaken ambitious environmental measures, demonstrate the financial strain associated with these initiatives. However, these challenges are not insurmountable; such investments often yield long-term gains through improved reputation, increased stakeholder trust, and enhanced operational efficiency.

The role of technological adoption and innovation is another critical dimension. Airports that integrate advanced technologies—such as automated systems, energy-efficient equipment, and digital platforms for optimizing resource use—are better positioned to align their inputs and outputs effectively. These practices not only support sustainability goals but also enhance financial performance by reducing waste and operational redundancies.

The analysis also identifies the importance of sustainability as a strategic priority. Airports that view environmental initiatives as integral to their long-term operational strategy are more likely to achieve consistent efficiency improvements. For instance, adopting frameworks such as the Airport Carbon Accreditation (ACA) program and investing in eco-friendly infrastructure have been pivotal for efficient airports like Sydney and Changi, enabling them to maintain full efficiency scores across multiple years.

The following sections will explore each inefficient airport in detail, focusing on their specific challenges and opportunities for improvement. These case studies will provide a comparative

analysis of performance metrics, sustainability initiatives, and the effectiveness of implemented measures. The ultimate goal is to offer actionable recommendations tailored to each airport's unique operational context, facilitating their transition to higher efficiency levels and enhanced sustainability outcomes.

4.3.2. SCHIPHOL AIRPORT TARGET INDICATORS OVERVIEW

Figure 6: Schiphol Airport.

Source: Independent.

Amsterdam Airport Schiphol, Figure 7, has demonstrated fluctuating efficiency levels over the years, and its target inputs and outputs reveal both strengths and challenges in achieving consistent optimal performance, Figure 8.

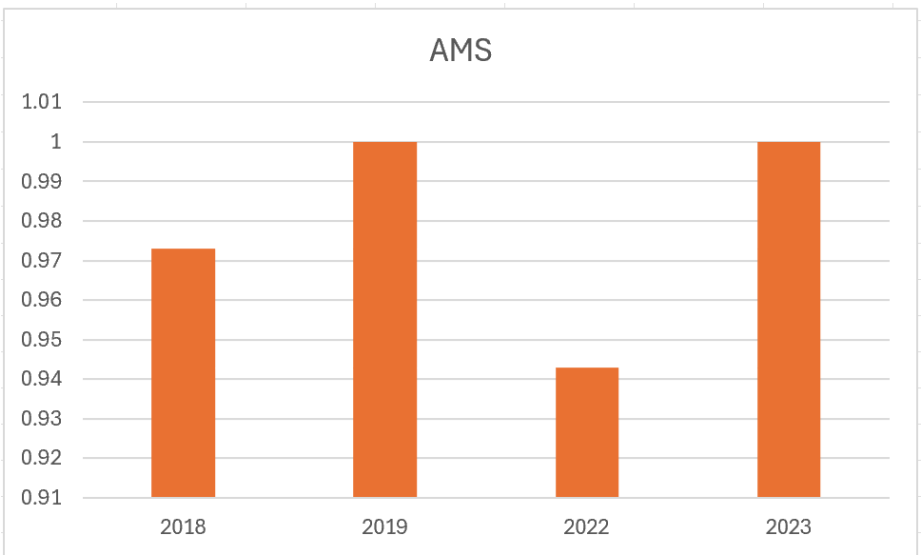

Figure 7: Efficiency of AMS over the years.

Source: Author.

Upon reviewing the data, it becomes evident that AMS performs exceptionally well in terms of sustainability, as its inputs have frequently met the target levels. This achievement highlights the airport's strong commitment to reducing its environmental impact and improving resource efficiency making this airport an example to be follow.

In terms of target outputs, it seems the focus on sustainability has come with significant financial costs, as reflected in the airport's output metrics. EBITDA decreased significantly from €552.45 million in 2018 to €304.50 million in 2023, remaining far from the target of €1,395.12 million in 2023 and drifting further from it over time. This indicates that sustainability initiatives may be impacting EBITDA due to the high costs of the solutions being implemented. However, it is also important to note that the decline in 2022 and 2023 could be linked to the effects of COVID-19 and the ongoing recovery of the aviation industry, which has not yet fully returned to pre-pandemic levels, as seen in other airports.

Passenger numbers, which in 2019, the best year for the industry, reached 71.68 million and met the target, have since declined to 61.89 million in 2023, although a recovery is evident when compared to 52.47 M in 2022. A similar trend is observed in aircraft movements, mirroring the pattern seen in passenger numbers, which suggests there is still room for recovery and growth.

It can be concluded that operational and financial outputs have not grown proportionally to the investments made in sustainability, indicating that the costs of implementing green initiatives have placed pressure on the airport's profitability and operational capacity. Additionally, the

impact of COVID-19 has added to these challenges as it can be witness by the airport's efficient performance in 2019 compared to 2022 and 2023.

To address these challenges, AMS must focus on improving its financial and operational outputs to complement its outstanding sustainability performance. This could involve marketing its sustainable performance to attract additional business opportunities, such as partnerships with sustainability conscious airlines or increased passenger traffic through marketing its green initiatives. Moreover, optimizing operational processes, such as restructuring flight schedules and enhancing terminal efficiency, could help increase passenger and aircraft handling capacity without damaging sustainability efforts used.

To sum up, AMS has made remarkable progress in sustainability, often performing at or near its target inputs. However, the high costs associated with these efforts highlight the need to balance environmental investments with strategies to improve financial and operational performance. By aligning its sustainability leadership with stronger economic outcomes, the airport can achieve consistent, long-term efficiency and success.

4.3.3. ISTANBUL AIRPORT TARGET INDICATORS OVERVIEW

Figure 8: Istanbul Airport.
Source: Daily Sabah.

Istanbul Airport, Figure 9, has clearly made progress over time in terms of efficiency, improving from 0.776 in 2019 to 0.979 in 2023. In terms of target inputs, the airport has shown improvement in direct emissions, reducing every year and reaching 19,611 tCO2 in 2023. Although it has not yet reached its target, progress has been made. For electricity consumption, waste generation, and water consumption, performance has been inconsistent, with decreases in some years and increases in others, rarely meeting the targets.

Target outputs have shown some progress, but financial and operational outputs still reveal room for improvement, as only in 2023 did EBITDA, passenger numbers, and aircraft movements reach their respective targets. EBITDA increased from €684.01 million in 2019 to €894.40 million in 2023. In terms of passenger numbers, the airport recorded 70.56 million passengers in 2019, aligning closely with its target, but numbers dropped sharply in 2022, likely due to the pandemic. By 2023, passenger numbers recovered to 76.03 million, meeting the target for that year. While this recovery demonstrates operational resilience, the decline in previous years highlights the possible impact of external disruptions, such as COVID-19, on the airport's efficiency. Similarly, aircraft movements increased from 329,900 in 2022 to 505,970 in 2023, fully meeting the target. Even though there is not enough data to confirm that the inefficiency in 2022 was solely due to the pandemic, as the airport has only been operational since 2019, it is evident that efficiency has improved over time, Figure 10.

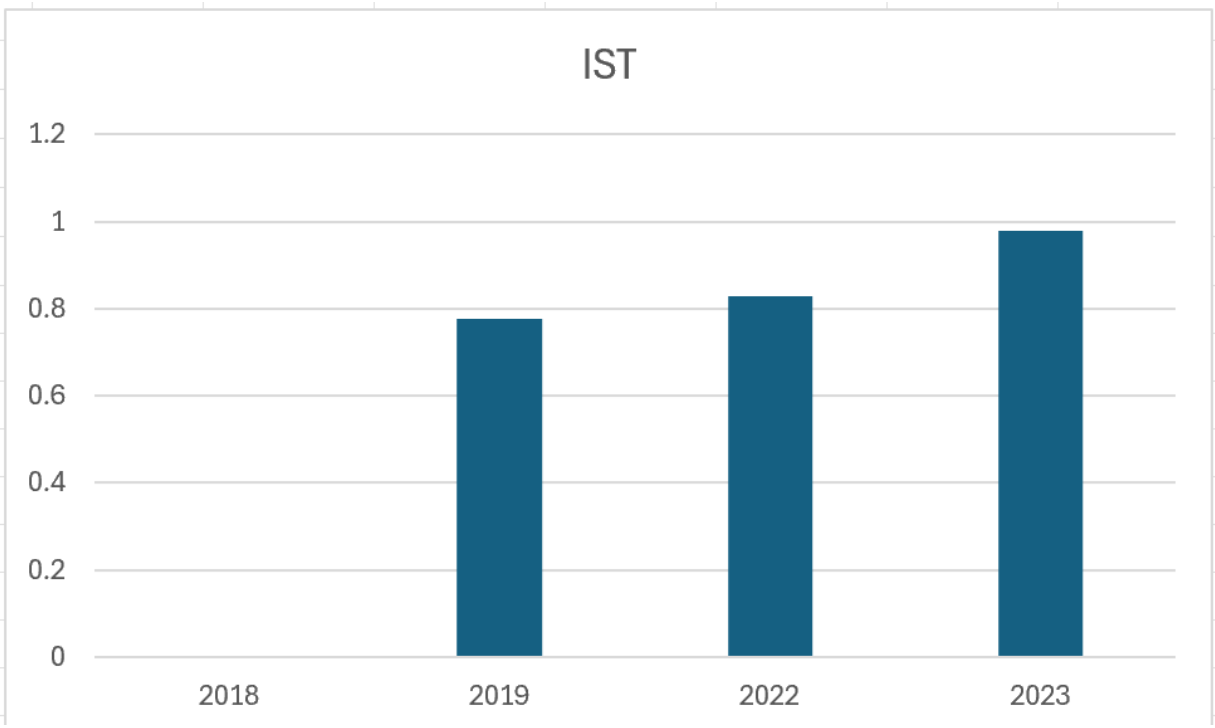

Figure 9: Efficiency of IST over the years.

Source: Author.

From the analysis of 2023, it is clear that the airport is on the right path. However, to align with the industry and become fully efficient, IST airport will need to continue investing in sustainability measures to meet its targets. At the same time, the airport must focus on financial and operational returns, as balancing these three crucial areas is key to overall success. The current inefficiencies can be partly justified by the fact that this airport is a relatively new, still in developing phase and learning from its errors.

4.3.4. BOSTON AIRPORT TARGET INDICATORS OVERVIEW

Figure 10: Boston Logan Airport.

Source: The New York Times.

Boston Logan International Airport, Figure 11, presents an interesting case in terms of efficiency. While the airport has demonstrated moments of strong performance, particularly in 2022 when it reached full efficiency, inefficiencies in financial and operational outputs are causing the airport to become inefficient and highlight areas that need improvement, Figure 12.

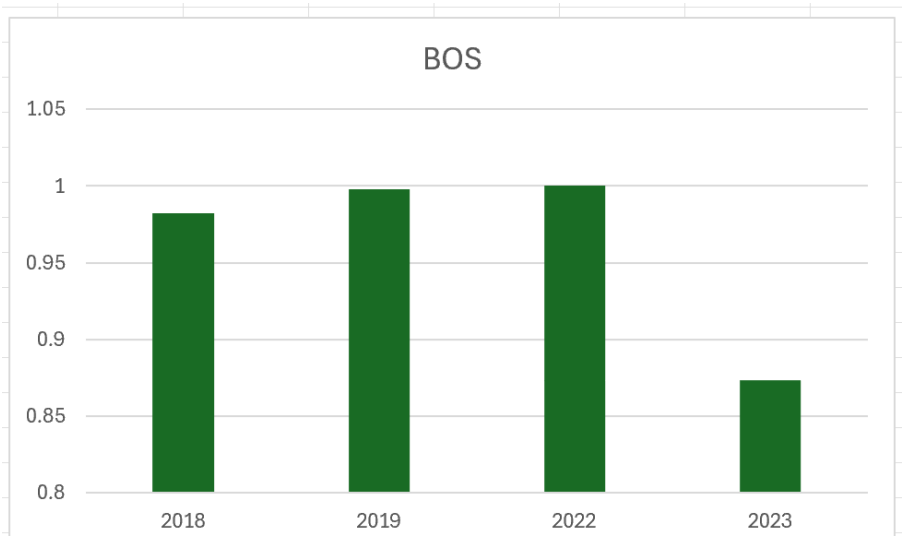

Figure 11: Efficiency of BOS over the years.

Source: Author.

In terms of target inputs, BOS has shown progress in reducing direct emissions, dropping significantly from 47,493 tCO2e in 2018 to 30,001 tCO2e in 2023, demonstrating a clear commitment to sustainability. However, despite this progress, emissions remained higher than the target of 7,250.04 tCO2e in 2023, indicating that additional measures are required to close this gap. Electricity consumption increased from 1,516,829,556 kWh in 2018 to 2,822,009,899 kWh in 2023, exceeding the target of 2,754,800,066 kWh. This indicates room for further optimization in energy use. Waste generation, while relatively stable, still exceeded targets, and water consumption saw significant fluctuations, reaching 768,663 m^3 in 2023, which met the target. These input trends reflect progress in some areas but highlight the need for consistent strategies to align with global performance standards and targets.

In terms of target outputs, BOS has experienced mixed results. EBITDA increased from €341.06 million in 2018 to €475.30 million in 2023, but it still fell short of the target of €1,054.30 million for 2023. Passenger numbers, which peaked at 41.90 million in 2019, dropped significantly to 31.10 million in 2022 but recovered to 39.20 million in 2023. While this is a positive trend, passenger numbers remain well below the 2023 target of 61.73 million, indicating that the airport has not yet fully regained its pre-pandemic levels. Similarly, aircraft movements followed a comparable pattern, with 396,540 movements recorded in 2023, which is below the target but reflects recovery after the pandemic.

Efficiency scores for BOS have fluctuated over the years, with strong performances in 2019 and 2022 when it achieved full efficiency. However, the decline on efficiency to 0.873 in 2023

suggests challenges in aligning inputs with outputs, particularly as the airport continues to deal with the effects of the pandemic and the high costs associated with sustainability investments.

The inefficiencies observed in BOS can be attributed to a combination of factors. The pandemic significantly disrupted passenger and aircraft operations, as seen in other airports. Additionally, the substantial investments in sustainability, while necessary, have likely placed financial strain on the airport, as evidenced by the slower growth in EBITDA compared to the resources allocated.

To address these challenges, the airport should focus on strategies that improve operational and financial performance while maintaining its commitment to sustainability. This could involve optimizing terminal and flight operations to increase passenger numbers and aircraft movements. Investing in revenue-generating services, such as retail, could help improve EBITDA without compromising the airport's environmental goals, as reflected in its participation in the ACA program. Additionally, accelerating the adoption of energy-saving technologies and improving waste and water management systems could reduce input variability and bring actual performance closer to target levels.

In conclusion, Boston Logan International Airport has demonstrated resilience in recovering from the pandemic and has made progress in sustainability. However, inefficiencies in aligning inputs and outputs, coupled with the high costs of sustainability initiatives, underscore the need for a more integrated approach to balance environmental, financial, and operational goals.

4.3.5. GUARULHOS AIRPORT TARGET INDICATORS OVERVIEW

Figure 12: Guarulhos Airport.

Source: ULMA.

The target inputs and outputs displayed in Tables 4 and 5 are critical for Guarulhos Airport's, Figure 13, improvement plan, highlighting inefficiencies that have worsened over time. These tables identify key focus areas by pinpointing specific inefficiencies and areas requiring immediate attention, such as emissions reduction and improved operational performance.

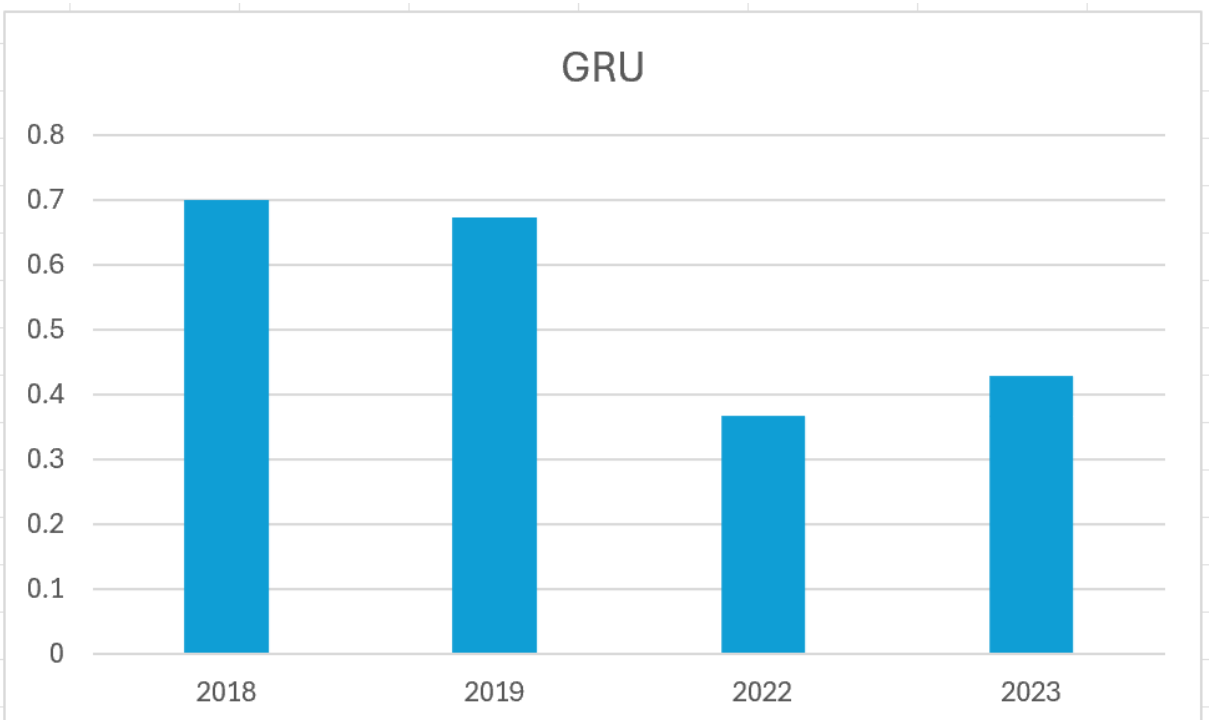

Figure 13: Efficiency of BOS over the years.

Source: Author.

The target inputs clearly show how much GRU needs to reduce its resource usage to become more efficient. Direct emissions require significant reductions, from an actual 28,359 tCO_2e in 2023 to the target of 17,011 tCO_2e, underlining the urgency for GRU to adopt carbon reduction strategies, such as renewable energy integration and operational efficiency improvements. Electricity consumption, which increased from 16,215,100 kWh in 2018 to 29,731,889 kWh in 2023, must also be optimized to meet the 2023 target of 29,527,638 kWh. Total waste generation increased from 11,346 metric tons in 2018 to 13,817 metric tons in 2023. While this value met the target in 2023, the increase over time is not a positive sign. Water consumption has also been rising, making continuous efforts to improve water management essential. These input targets highlight the critical need for GRU to implement sustainability measures to achieve efficiency, Figure 14.

The target outputs further underscore the areas where GRU must improve its operational and financial performance. For EBITDA, GRU showed progress, increasing from €297.12 million in 2018 to €397.88 million in 2023. However, this is still far from the target of €1,603.98 million for 2023, signalling a significant gap in financial performance. Similarly, passenger numbers have remained stable but are well below the 2023 target, as are aircraft movements. These output targets emphasize the urgent need for GRU to act on the operational and financial aspects of the airport to align with its goals.

The absence of an ACA level score is not due to inefficiency but rather because GRU is not part of the Airport Carbon Accreditation program. Joining this program would be a crucial step in demonstrating and strengthening GRU's commitment to sustainability and carbon management, thereby enhancing its reputation as an environmentally responsible airport.

To sum up, it is essential for Guarulhos Airport to take immediate action, as it is significantly behind the targets established for 2023. This lag reflects a lack of sustainability commitment and underscores the long path ahead for GRU to achieve efficiency.

4.4. SWOT ANALYSIS

For the SWOT analysis, the DEA results, the data used for the DEA analysis, and information available on the airport website were used to construct this SWOT analysis. This analysis will be conducted for the four inefficient airports according to DEA analysis, as well as for Changi Airport to compare with an efficient airport.

4.4.1. SCHIPHOL AIRPORT

Schiphol Airport, one of Europe's leading aviation hubs, plays a fundamental role in connecting the country to the world and facilitating economic growth. However, like many major airports, it faces the challenge of maintaining operational efficiency while meeting ambitious sustainability goals. This SWOT analysis provides an in-depth evaluation of Schiphol's internal strengths and weaknesses, as well as the external opportunities and threats that influence its performance.

The analysis aims to identify actionable strategies that can help Schiphol balance its financial objectives with its commitment to environmental sustainability.

Strengths

1. Sustainability Initiatives: Schiphol Airport has demonstrated a strong commitment to sustainability, including achieving high accreditation levels under the Airport Carbon Accreditation program. This highlights its proactive attitude in implementing green practices.
2. Consistent Passenger Flow: The airport has consistently managed high passenger numbers, reflecting its status as a major hub in Europe and its strong market position in global aviation.

3. Innovative Practices: Schiphol has adopted innovative solutions in sustainability, such as energy efficient operations and waste management systems, which align with its strategic priorities.
4. Geographical Advantage: Its central location in Europe positions Schiphol as a key transit hub, providing access to a large number of destinations and a competitive advantage in the aviation industry.

Weaknesses

1. Financial Strain: Sustainability initiatives, while essential, have imposed significant financial costs on the airport, as evidenced by fluctuating EBITDA levels over the years.
2. Inconsistent Efficiency: Although Schiphol has achieved full efficiency in certain years, its performance has been inconsistent, reflecting challenges in balancing operational efficiency with sustainability investments.
3. Resource Utilization: Areas such as energy consumption and waste generation occasionally exceed targets, indicating the need for further optimization.
4. Pandemic Recovery: Like many airports, Schiphol has faced challenges recovering to pre-pandemic passenger and operational levels, which has impacted its financial performance.

Opportunities

1. Growing Demand for Sustainability: Increasing consumer and airline demand for environmentally responsible practices presents an opportunity for Schiphol to market itself as a leader in sustainable aviation.
2. Regulatory Support: The European Union's stringent sustainability regulations provide a framework for Schiphol to strengthen its environmental initiatives and secure funding or incentives.
3. Technology Integration: Advances in green technologies, such as renewable energy systems and AI-driven resource optimization tools, could help the airport further reduce its environmental footprint and improve efficiency.
4. Partnership Opportunities: Collaborations with sustainability-focused airlines and stakeholders could enhance Schiphol's reputation and attract environmentally conscious travelers and businesses.

Threats

1. High Operational Costs: The significant upfront investment required for sustainability measures continues to be a financial challenge, potentially affecting profitability and competitiveness.
2. Regulatory Pressure: While regulations can be an opportunity, they also establish risks if Schiphol fails to meet developing standards, leading to penalties or reputational damage.
3. Market Competition: Competing airports with similar capabilities, such as Frankfurt and Heathrow, could limit Schiphol's ability to attract passengers and business partners.
4. Economic Instability: Fluctuations in global economic conditions, including recessions or inflation, could reduce air travel demand and impact the airport's revenue.

Strategic Recommendations

1. Optimize Resource Management

Schiphol Airport should intensify its efforts to optimize resource usage by adopting advanced technologies and implementing more efficient operational practices. This includes investing in smart energy management systems to monitor and reduce electricity consumption and upgrading waste management practices to minimize landfill contributions. Renewable energy sources, such as solar panels or wind turbines, should be prioritized to reduce reliance on non-renewable energy. Additionally, Schiphol could explore innovative water recycling and conservation systems to further reduce its environmental footprint. By integrating these technologies, the airport can align its resource usage with sustainability goals while reducing operating costs over the long term. Even though the airport it is consider very sustainable there is always room for improvement and investments on the matter should not stop as the airport can easily fall behind due to technology evolution.

2. Strengthen Financial Resilience

To mitigate the financial strain of sustainability initiatives, Schiphol should diversify its revenue streams. This can include expanding commercial offerings within the airport, such as retail, dining, and entertainment options, to increase non-aeronautical revenue. The airport could also consider leasing spaces to sustainability focused businesses, creating an association between its green objectives and revenue generation. Developing

premium services, such as exclusive lounges or eco-friendly travel packages, could attract high-value travellers while emphasizing Schiphol's commitment to sustainability. Additionally, monetizing sustainability efforts such as offering consultancy services to other airports or charging lower landing fees for airlines using sustainable practices could further strengthen its financial resilience.

3. **Influence Sustainability Leadership**

   Schiphol Airport's leadership in sustainability presents an opportunity to enhance its brand and attract environmentally conscious airlines, businesses, and travellers. Marketing campaigns should focus on highlighting Schiphol's achievements in areas such as carbon neutrality, waste reduction, and renewable energy adoption. Developing partnerships with eco-friendly airlines and offering incentives for sustainable operations such as discounted landing fees for airlines meeting specific carbon reduction targets can further reinforce this position. Schiphol should also communicate its sustainability initiatives to passengers through clear signage, educational campaigns, and digital platforms, fostering an image of an environmentally responsible airport.

4. **Enhance Collaborative Efforts**

   Collaboration with regulatory bodies and research institutions can help Schiphol access the funding, expertise, and technology needed to achieve its goals further. The airport should engage with European Union sustainability programs and initiatives to secure financial incentives or grants for green projects. Partnerships with technology companies specializing in green innovations, such as AI driven efficiency tools or renewable energy providers, can accelerate progress in reducing resource consumption. Additionally, Schiphol should actively participate in global aviation forums and networks to share best practices, learn from other airports, and strengthen its position as a global sustainability leader.

4.4.2. ISTANBUL AIRPORT

Istanbul Airport, a key aviation hub connecting Europe, Asia, and the Middle East, has rapidly established itself as one of the largest and most modern airports in the world. Its strategic location and advanced infrastructure position the airport as a critical player in global aviation. However, as a relatively new airport, it faces unique challenges in balancing rapid growth, operational efficiency, and sustainability goals. This SWOT analysis provides an in-depth

evaluation of Istanbul Airport's internal strengths and weaknesses, along with external opportunities and threats, to identify strategic routes for improvement and long-term success.

Strengths

1. Modern Infrastructure: As a newly constructed airport, Istanbul Airport boasts modern infrastructure and cutting-edge technology, making it one of the most advanced airports globally.
2. Strategic Location: Its geographical position provides a significant advantage, acting as a key hub connecting Europe, Asia, and the Middle East, which enhances its passenger and cargo traffic potential.
3. High Capacity: Designed to handle a large volume of passengers and aircraft movements, Istanbul Airport has the capacity to grow and accommodate increasing air traffic demand.
4. Commitment to Sustainability: The airport has shown improvement in efficiency over the years, with progress in areas like reducing direct emissions and waste management.

Weaknesses

1. High Operational Costs: Sustainability measures and modern infrastructure require substantial investments, posing financial challenges in maintaining profitability while achieving environmental goals.
2. Inconsistent Resource Management: Data reveals fluctuations in energy consumption, waste generation, and water usage, indicating the need for more consistent and efficient resource utilization.
3. Limited Experience as a New Airport: As a relatively new entrant, the airport is still in its developmental phase, learning to balance operational efficiency with sustainability efforts.
4. Dependence on External Recovery: Like other global airports, Istanbul Airport's recovery from the pandemic has been gradual, with passenger traffic and operational metrics taking time to stabilize.

Opportunities

1. Growing Regional Connectivity: Istanbul Airport's strategic location positions it to become a major regional hub, capturing increased demand for air travel in Europe, Asia, and the Middle East.
2. Technological Advancements: Opportunities exist to integrate smart systems and renewable energy technologies to enhance efficiency and reduce resource consumption.
3. Tourism and Trade Growth: Turkey's growing tourism industry and its role as a trade hub provide opportunities for the airport to attract more passengers and cargo operations.
4. Collaborations and Incentives: Partnerships with sustainability focused organizations and access to international funding or incentives can support green initiatives and operational enhancements.

Threats

1. Economic Instability: Economic fluctuations in Turkey or globally could impact passenger demand and revenue streams.
2. Regulatory Challenges: Increasingly stringent environmental regulations might require additional investments, straining financial resources further.
3. Competition from Regional Airports: Airports in the region, such as Doha and Dubai, pose significant competition in attracting airlines and passengers.
4. Global Disruptions: Future crises, such as pandemics or geopolitical tensions, could disrupt operations and slow progress toward achieving sustainability goals.

Strategic Recommendations for Istanbul Airport

1. **Optimize Resource Management**

   Istanbul Airport should prioritize initiatives to reduce resource consumption and improve efficiency. This includes adopting smart energy management systems to monitor and control electricity usage, investing in renewable energy sources like solar or wind, and enhancing waste and water management systems. These efforts will not only reduce environmental impact but also lower operational costs over time.

2. **Strengthen Financial Resilience**

To manage the financial strain of sustainability initiatives, Istanbul Airport should explore new revenue streams. Expanding retail and dining options within the airport, creating eco-friendly premium services, and attracting high-value travelers through targeted marketing campaigns can increase non-aeronautical revenue. Additionally, developing Istanbul Airport as a destination for conferences and exhibitions can capitalize on its modern infrastructure and strategic location.

3. **Leverage Sustainability Leadership**

   The airport's ongoing sustainability efforts should be actively promoted to enhance its reputation as an environmentally conscious hub. Partnerships with airlines that focus on sustainable aviation, along with incentives like reduced landing fees for those adopting green practices, can help strengthen its brand. Publicizing sustainability achievements through campaigns and interactive displays will also engage passengers and stakeholders.

4. **Enhance Collaborative Efforts**

   Collaboration with government agencies, private stakeholders, and international organizations can provide the airport with funding, expertise, and innovative technologies. Leveraging partnerships with global aviation sustainability networks can facilitate the sharing of best practices and enhance its global standing. Istanbul Airport should also engage with regional and international sustainability programs to secure grants or incentives for its environmental initiatives.

4.4.3. BOSTON AIRPORT

Boston Logan International Airport, a major hub in the United States of America, serves as a critical airport for both domestic and international travel. With its strategic location near key metropolitan areas and its role in driving regional economic activity, the airport holds significant importance in the aviation world. However, like many major airports, BOS faces challenges in improving efficiency, aligning sustainability goals, and managing increasing passenger demand. This SWOT analysis evaluates the airport's internal strengths and weaknesses, as well as external opportunities and threats, and offers strategic recommendations to enhance its operational performance and environmental stewardship.

Strengths

1. Strong Regional Presence: Boston Logan is the largest airport in New England, serving as a vital hub for both domestic and international flights and capturing a significant share of regional air traffic.
2. Proximity to Key Markets: Its location near Boston and other major metropolitan areas provides easy access to a large, affluent customer base and strong business travel demand.
3. Established Infrastructure: The airport has a well-developed infrastructure, including terminals with modern amenities and efficient airfield operations.
4. Environmental Initiatives: Boston Logan has made strides in sustainability, including reducing greenhouse gas emissions and adopting energy-efficient building standards.

Weaknesses

1. Congestion and Capacity Constraints: High passenger volumes often lead to congestion and delays, particularly during peak travel times.
2. Aging Infrastructure in Some Areas: Despite modernization efforts, certain terminals and facilities require further upgrades to meet evolving operational demands.
3. Limited Renewable Energy Adoption: While progress has been made, the airport still relies heavily on traditional energy sources, limiting its sustainability progress.
4. Financial Pressures: The costs associated with implementing sustainability initiatives and infrastructure upgrades place pressure on financial resources.

Opportunities

1. Rising Demand for Sustainable Aviation: Growing consumer and airline interest in environmentally friendly practices creates opportunities for Boston Logan to enhance its sustainability profile.
2. Technological Advancements: New technologies in energy efficiency, waste management, and operational optimization can improve resource management and reduce costs.
3. Strategic Partnerships: Collaborations with airlines, technology providers, and governmental agencies can accelerate the adoption of innovative solutions and secure funding for sustainability projects.

4. Expansion Opportunities: The growing demand for air travel in the region provides opportunities for infrastructure expansion and increased passenger services.

Threats

1. Competitive Pressure: Other regional airports, such as New York's JFK and Newark, pose significant competition for passengers and airline partnerships.
2. Regulatory Challenges: Increasingly stringent environmental and safety regulations could add operational costs and complexity.
3. Economic Instability: Economic downturns or recessions could reduce air travel demand and impact revenue streams.
4. Climate Risks: The airport's coastal location makes it vulnerable to climate-related threats such as rising sea levels and extreme weather events.

Strategic Recommendations

1. **Optimize Resource Management**

   To improve operational efficiency and sustainability, Boston Logan should invest in advanced resource management systems. This includes energy monitoring technologies to reduce electricity usage and modern waste management systems to minimize landfill contributions. The airport should also explore renewable energy sources, such as installing solar panels on terminal rooftops or partnering with local renewable energy providers to offset its carbon footprint. Additionally, water conservation measures, such as rainwater harvesting and greywater recycling, could be introduced to further optimize resource usage.

2. **Expand and Modernize Infrastructure**

   Boston Logan should prioritize upgrading older terminals and expanding capacity to reduce congestion and enhance passenger experience. Terminal upgrades should incorporate sustainable building practices, such as energy-efficient lighting and HVAC systems. Expanding airfield capacity or adding gates to accommodate growing passenger demand could also alleviate delays during peak travel periods. Furthermore, integrating automated systems for baggage handling and passenger check-ins can improve operational efficiency.

3. **Leverage Sustainability as a Competitive Advantage**

The airport's commitment to environmental initiatives should be actively marketed to enhance its reputation as a leader in sustainable aviation. This includes highlighting achievements, such as emission reductions and energy-efficient terminal designs, through public campaigns and partnerships with environmentally conscious airlines. Offering incentives, such as reduced landing fees for airlines that use sustainable aviation fuels, can further position Boston Logan as a forward-thinking airport.

4. **Strengthen Financial Resilience**

   To support the costs of sustainability and modernization efforts, the airport should explore diversifying revenue streams. This includes expanding non-aeronautical revenue through improved retail and dining options and introducing premium services such as eco-friendly lounges or priority lanes for business travellers. Boston Logan should also seek funding opportunities from government programs, such as grants for green projects or partnerships with private investors focused on sustainability.

5. **Enhance Strategic Collaborations**

   Collaborations with regional stakeholders, including local governments, universities, and private companies, can accelerate the adoption of innovative sustainability solutions. Partnering with technology providers to implement AI-driven tools for optimizing flight schedules and energy use can improve efficiency. The airport should also engage in global aviation sustainability forums to exchange best practices and strengthen its position as an industry leader.

6. **Mitigate Climate Risks**

   Given its coastal location, Boston Logan should proactively address climate-related threats by investing in climate resilience measures. This includes elevating critical infrastructure to protect against sea-level rise, improving stormwater management systems, and conducting regular assessments of climate vulnerabilities. Partnering with environmental experts and governmental agencies can help the airport develop comprehensive climate adaptation strategies.

4.4.4. GUARULHOS AIRPORT

Guarulhos International Airport, located in Brazil, is the largest airport in the country and a critical hub for both domestic and international travel across South America. As a major entry to Brazil, Guarulhos plays a vital role in connecting the region with global markets and

supporting the country's tourism and trade industries. However, like many large airports, it faces challenges in managing increasing passenger traffic and EBITDA, maintaining operational efficiency, and meeting sustainability goals. This SWOT analysis evaluates GRU's internal strengths and weaknesses, along with external opportunities and threats, and provides strategic recommendations to enhance its performance and environmental standards.

Strengths

1. Strategic Location: GRU's location in São Paulo, one of South America's largest metropolitan areas, provides access to a vast passenger base and key business markets.
2. High Passenger Volume: As Brazil's busiest airport, GRU benefits from strong demand for both domestic and international travel, solidifying its position as a critical regional hub.
3. Operational Capacity: GRU has the infrastructure to handle significant passenger and cargo volumes, with multiple terminals and airfield capacity to accommodate growth.
4. Regional Influence: GRU serves as a key hub for connecting South America with other continents, particularly North America and Europe.

Weaknesses

1. Aging Infrastructure: Despite recent expansions, some areas of the airport still rely on outdated infrastructure, limiting efficiency and passenger experience.
2. Limited Sustainability Initiatives: GRU has yet to fully integrate renewable energy and waste reduction programs, lagging behind global counterparts in environmental performance.
3. Congestion During Peak Periods: High passenger volumes often lead to delays and overcrowding, particularly during peak travel times.
4. Financial Constraints: Limited access to international funding and reliance on local economic conditions pose challenges for large-scale sustainability and modernization projects.

Opportunities

1. Tourism Growth in Brazil: Brazil's expanding tourism sector offers opportunities for GRU to attract more international airlines and passengers.

2. Sustainability Trends: Growing demand for environmentally responsible operations provides GRU with an opportunity to develop green initiatives and market itself as a sustainable airport.
3. Technological Advancements: New technologies, such as AI-driven efficiency tools and renewable energy systems, can help the airport improve operations and reduce costs.
4. Partnerships and Investments: Collaborating with private investors, government agencies, and global organizations could provide funding and expertise for large-scale projects.

Threats

1. Economic Volatility: Brazil's economic instability and fluctuations in exchange rates could affect passenger demand and operational costs.
2. Competition from Regional Airports: Other major airports in South America, such as Bogotá and Santiago, are competing for international airline partnerships and passenger traffic.
3. Regulatory Pressures: Increasingly stringent environmental regulations may require significant investments in sustainability measures, impacting profitability.
4. Global Crises: External disruptions such as pandemics or geopolitical tensions could reduce air travel demand and slow progress on operational improvements.

Strategic Recommendations

1. **Optimize Resource Management**

   GRU should prioritize improving resource efficiency by adopting advanced energy management and waste reduction systems. Investing in renewable energy sources, such as solar panels and biofuels, would reduce reliance on traditional energy while lowering operational costs. Enhanced water management systems, including rainwater harvesting and recycling, could help address resource constraints. Integrating these measures into daily operations would align GRU with global sustainability trends and improve its efficiency.

2. **Modernize Infrastructure**

Addressing aging infrastructure is critical for GRU to meet growing passenger demands and improve operational efficiency. Upgrading terminals with modern amenities and sustainable building materials would enhance the passenger experience while reducing environmental impact. Expanding airfield capacity and streamlining baggage handling systems could alleviate congestion during peak periods. Additionally, introducing automated check-in systems and digital wayfinding solutions would further enhance operational performance and customer satisfaction.

3. **Leverage Sustainability as a Competitive Advantage**

GRU should position itself as a leader in sustainability within South America by showcasing its commitment to environmental responsibility. This can include publicizing sustainability achievements through campaigns, such as emission reductions or renewable energy adoption, and partnering with environmentally conscious airlines. Offering incentives, such as reduced fees for airlines adopting sustainable practices, would reinforce this commitment while attracting new partnerships. Passenger engagement through educational campaigns on sustainability could also strengthen GRU's image as a forward-thinking airport.

4. **Diversify Revenue Streams**

To address financial constraints, GRU should expand its non-aeronautical revenue opportunities. This includes enhancing retail and dining options, particularly with local and international brands, to increase passenger spending. Developing premium services, such as VIP lounges, eco-friendly travel packages, and conference facilities, could attract high-value travelers. Collaborations with private investors to fund green initiatives would further alleviate financial pressures while accelerating progress on sustainability projects.

5. **Enhance Collaboration with Stakeholders**

GRU should actively collaborate with government agencies, private companies, and global organizations to secure funding and expertise for its sustainability efforts. Partnerships with technology providers could facilitate the adoption of AI-driven systems for flight scheduling, energy use optimization, and passenger flow management. Participation in international sustainability programs and aviation forums

would allow GRU to learn from global best practices and position itself as a leader in sustainable aviation.

6. Mitigate Risks from Economic and Environmental Pressures

   GRU must proactively address economic and environmental risks by developing long-term strategies to increase resilience. This includes diversifying revenue streams to reduce reliance on passenger traffic during economic downturns and implementing climate adaptation measures, such as flood control systems and infrastructure designed to withstand extreme weather events. Collaborating with environmental experts and regional governments can help GRU develop comprehensive strategies for addressing these challenges.

4.4.5 CHANGI AIRPORT

Unlike the other airports the SWOT analysis was done before Changi Airport, located in Singapore, is widely recognized as one of the most efficient and well-managed airports in the world. Known for its outstanding facilities, perfect passenger experience, and commitment to innovation, Changi has set targets for excellence in the aviation industry. Despite its status as a global leader, the airport must continually address emerging challenges, such as adapting to new sustainability expectations, increasing passenger demands, and maintaining its competitive edge. This SWOT analysis evaluates Changi Airport's strengths, weaknesses, opportunities, and threats and provides strategic recommendations to sustain its position as a leading aviation hub while advancing its sustainability and operational goals.

Strengths

1. World-Class Facilities: Changi is renowned for its modern, state-of-the-art infrastructure and exceptional passenger amenities, including the iconic Jewel Changi Airport.
2. Operational Efficiency: The airport consistently achieves high efficiency scores, demonstrating its ability to manage resources effectively while delivering superior service.
3. Strong Global Connectivity: Changi serves as a major hub connecting Asia to the rest of the world, with a vast network of international flights.
4. Commitment to Innovation: The airport is at the forefront of adopting advanced technologies, such as automated check-in systems and robotics, to enhance operations.

5. Proactive Sustainability Efforts: Changi has made significant strides in integrating sustainability measures, such as energy-efficient infrastructure and carbon reduction initiatives.

Weaknesses

1. High Operating Costs: Maintaining world-class facilities and implementing advanced sustainability measures require significant financial resources.
2. Space Constraints: As a land-scarce country, Singapore faces challenges in expanding the airport to meet future growth without significant infrastructure investment.
3. Dependence on Global Connectivity: Changi's success heavily relies on its role as a transit hub, making it vulnerable to disruptions in international travel demand.
4. Limited Renewable Energy Infrastructure: While progress has been made, further opportunities exist to expand the use of renewable energy across airport operations.

Opportunities

1. Growth in Asian Aviation Market: The rising demand for air travel in Asia provides Changi with opportunities to expand its network and strengthen its position as a regional hub.
2. Sustainability Leadership: Changi can leverage its existing efforts to position itself as a global leader in sustainable aviation, setting benchmarks for other airports.
3. Technological Advancements: Continued integration of cutting-edge technologies, such as AI-driven operational tools and renewable energy systems, can further improve efficiency and sustainability.
4. Partnership Opportunities: Collaborations with airlines, technology providers, and global organizations can enhance innovation and provide funding for new projects.

Threats

1. Intense Regional Competition: Airports like Hong Kong, Incheon, and Kuala Lumpur pose significant competition for passengers and airline partnerships.
2. Global Economic Instability: Economic downturns or geopolitical tensions can reduce passenger demand and impact revenue streams.

3. Climate Risks: As a coastal facility, Changi faces potential threats from rising sea levels and extreme weather events.
4. Evolving Regulatory Requirements: Stricter environmental regulations could increase operational costs and require additional investment in sustainability measures.

Strategic Recommendations

1. **Enhance Sustainability Leadership**

   Changi Airport should continue to build on its sustainability initiatives to solidify its position as a global leader in green aviation. This includes expanding the use of renewable energy, such as solar panels on rooftops and airfield areas, and exploring biofuel partnerships with airlines. The airport could also implement more comprehensive waste management systems, including recycling programs and waste-to-energy technologies. Highlighting these efforts through public campaigns and stakeholder engagement will strengthen Changi's reputation as an environmentally conscious hub.

2. **Leverage Technological Innovation**

   To maintain its operational edge, Changi should continue integrating advanced technologies into its operations. AI-driven tools for resource optimization, predictive maintenance, and passenger flow management can further enhance efficiency. The airport could also explore the use of autonomous vehicles for ground operations and robotics for cleaning and baggage handling, reducing costs and improving performance. Partnerships with technology providers and research institutions can accelerate the adoption of innovative solutions.

3. **Address Space Constraints with Smart Planning**

   As Singapore is land-scarce, Changi should focus on maximizing the use of its existing space through innovative designs and technologies. Modular terminal designs and multi-level operational areas can help address capacity constraints. The airport could also explore virtual queueing systems and advanced scheduling tools to reduce congestion during peak periods. Long-term expansion plans, such as Terminal 5, should incorporate sustainable building materials and energy-efficient technologies.

4. **Strengthen Resilience Against Global Risks**

Changi should develop comprehensive strategies to mitigate risks associated with global disruptions, such as pandemics or economic instability. Diversifying revenue streams through non-aeronautical income, such as retail, entertainment, and real estate development, can reduce reliance on passenger traffic. Investing in climate resilience measures, such as elevated infrastructure and improved stormwater management, will also help protect the airport from potential climate-related impacts.

5. Expand Regional and Global Partnerships

   Changi should deepen collaborations with regional stakeholders, airlines, and governments to strengthen its position as a transit hub. Strategic partnerships with airlines that prioritize sustainability, such as those adopting sustainable aviation fuels or carbon-neutral operations, can align with Changi's environmental goals. Participation in global aviation forums and sustainability programs will help Changi maintain its leadership role and influence industry-wide best practices.

6. Enhance Passenger Experience as a Competitive Edge

   While Changi already excels in passenger satisfaction, it should continue innovating to stay ahead of competitors. Investments in digital experiences, such as personalized travel apps and virtual assistants, can enhance convenience for travelers. Expanding the range of unique offerings, such as cultural showcases, art installations, and eco-friendly lounges, will further differentiate Changi from its competitors and enhance its global reputation.

4.4.6 OVERVIEW OF SWOT ANALYSIS

The SWOT analyses for Schiphol Airport, Istanbul Airport, Boston Logan International Airport, Guarulhos International Airport, and Changi Airport reveal critical insights into the common challenges and opportunities faced by global aviation hubs, as well as unique differences between efficient and inefficient airports. While all these airports are major players in their regions, their performance levels, sustainability initiatives, and operational strategies diverge significantly, resulting in varying degrees of efficiency and resilience.

Common Themes Across Airports

1. Sustainability Efforts:

All the airports recognize the importance of sustainability, though their progress varies. Airports like Schiphol and Changi have taken significant strides in reducing their carbon footprints and adopting renewable energy systems, while others, like Guarulhos and Istanbul, are still in the developmental phase of their sustainability initiatives.

2. Financial Constraints:

   The cost of implementing sustainability measures and modernizing infrastructure is a common challenge, particularly for airports like Guarulhos and Boston Logan, where financial pressures limit the pace of upgrades. Even efficient airports like Changi face high operating costs to maintain their world-class facilities and sustainability programs.

3. Technological Advancements:

   Advances in green technologies and AI-driven tools provide opportunities for all five airports to enhance efficiency and sustainability. Efficient airports like Changi are already leveraging these technologies, while others are still exploring their potential.

4. Global Risks and Climate Challenges:

   Economic volatility, global disruptions like pandemics, and climate risks, such as rising sea levels and extreme weather events, pose significant threats to all airports, emphasizing the need for resilience-building measures.

Differences Between Efficient and Inefficient Airports

1. **Efficiency Levels:**

   Changi Airport stands out as the most efficient airport in this group of five, consistently achieving high efficiency scores through its operational excellence, advanced infrastructure, and innovative practices. Conversely, airports like Guarulhos and Istanbul, while strategically located, face inefficiencies due to aging infrastructure, inconsistent resource management, and fluctuating operational performance.

2. **Sustainability Integration:**

   Efficient airports like Changi and Schiphol are leaders in sustainability, integrating renewable energy, waste management, and carbon reduction initiatives into their operations. In contrast, Guarulhos and Istanbul are still developing comprehensive sustainability programs, lagging behind their global counterparts.

3. **Passenger Experience and Infrastructure:**

Changi Airport excels in providing a seamless passenger experience through its world-class amenities, innovative designs, and customer-centric approach. Boston Logan and Schiphol also offer well-developed infrastructure but face congestion and aging facilities in certain areas. Guarulhos and Istanbul, while large in capacity, must address infrastructure inefficiencies to meet growing passenger demands effectively.

4. **Regional Challenges:**

   Economic instability and regulatory pressures are particularly challenging for airports like Guarulhos and Istanbul, which operate in regions with volatile economic conditions. Conversely, Schiphol and Boston Logan benefit from more stable regulatory environments, although they face intense competition from neighboring hubs.

Strategic Outlook

The analyses highlight a clear distinction between efficient airports, such as Changi, and airports striving to improve, such as Guarulhos and Istanbul. Efficient airports succeed through strategic integration of sustainability, innovation, and passenger-focused design, while inefficient airports face operational challenges stemming from infrastructure gaps, resource mismanagement, and financial constraints.

To bridge this gap, inefficient airports must prioritize investments in modernizing infrastructure, adopting advanced technologies, and strengthening sustainability efforts. Collaboration with stakeholders and global forums can accelerate this progress by providing access to funding and expertise. Efficient airports, on the other hand, should focus on maintaining their competitive edge by continuously innovating and addressing emerging challenges, such as climate risks and rising passenger demands.

Ultimately, the path to sustained excellence lies in balancing operational efficiency with environmental stewardship, financial resilience, and a commitment to enhancing passenger experience. By learning from the successes and challenges of each airport, the global aviation industry can move closer to achieving a more sustainable and efficient future.

4.5. IMPLICATIONS FOR EFFICIENCY

The analysis reinforces the role of sustainability in achieving efficiency, as airports with structured sustainability strategies outperformed airports with high values on sustainability measures. Efficient airports serve as benchmarks, demonstrating that sustainability investments are compatible with good financial and operational results.

The study's research question (How do sustainability measures impact the financial dynamics of major airports, and what factors contribute to the variations observed?) can be answered with this study.

Sustainability measures can negatively impact the financial dynamics of major airports in the initial stages due to the substantial investments required for their implementation. Airports with robust sustainability measures, such as high Airport Carbon Accreditation (ACA) levels, lower emissions, efficient waste management, and optimized electricity and water consumption, often face challenges in maintaining financial and operational efficiency in the short term. For example, Amsterdam Airport and Istanbul Airport, which achieved two of the highest ACA levels in 2023, still fluctuated between efficiency and inefficiency during the analysed period. Although Amsterdam Airport reached full efficiency in 2023, its earlier performance demonstrates that the financial and operational burdens of high sustainability investments can delay efficiency gains. Istanbul Airport, despite being relatively new, has shown consistent improvement in efficiency every year since its opening in 2019. This upward trend, connected with a steady increase in EBITDA, highlights those high investments in sustainability, while initially costly, end up having a return in the long-term financial and operational benefits.

The example of Sydney Airport, which consistently maintained a level 3 accreditation and remained efficient throughout the years analysed, further underscores the importance of sustained effort and strategic execution. These findings suggest that while sustainability measures may initially strain financial and operational resources, the long-term benefits, such as cost savings through energy efficiency, enhanced reputation, and increased stakeholder trust, help airports achieve greater efficiency and profitability over time. Istanbul Airport’s improvement demonstrates that even airports initially burdened by high investments in sustainability can, over time, align their operations to achieve both efficiency and profitability.

Several factors contribute to the variations observed among airports in their journey toward efficiency. One significant factor is the high upfront cost of sustainability initiatives, which impacts financial and operational performance due to increased operational expenses. These costs include adopting green technologies, upgrading infrastructure to meet sustainability standards, and securing certifications such as the ACA. For instance, transitioning to renewable energy sources or implementing advanced waste management systems often requires significant financial spending that may not have immediate returns. Additionally, these investments often demand organizational changes, staff training, and new operational protocols, which can further pressure resources in the short term.

Another key factor is strategic prioritization, which can heavily influence the success of sustainability efforts. Airports that integrate sustainability into their core strategies and carefully plan their investments tend to mitigate inefficiencies more effectively. This involves identifying critical areas for improvement, such as energy consumption or emissions reduction, and addressing these issues in a phased, organized manner. For instance, by prioritizing high-impact initiatives such as installing energy-efficient lighting or optimizing water recycling systems, airports can achieve tangible results early on, building momentum and support for further investments. Moreover, a strategic approach ensures that resources are allocated efficiently, reducing the likelihood of inefficiencies between sustainability goals and operational capabilities.

Regulatory frameworks and stakeholder expectations also play a critical role in shaping airport efficiency. Airports in regions with strong environmental regulations, such as the European Union, are often compelled to adopt sustainability measures earlier, which can initially strain resources but ultimately contribute to long-term efficiency. Furthermore, increasing consumer awareness and investor demand for sustainable practices create external pressures that encourage airports to prioritize green initiatives. Airports that respond proactively to these pressures, such as Changi Airport in Singapore, not only meet regulatory requirements but also enhance their market competitiveness by appealing to environmentally conscious travellers and partners (airlines).

Hypothesis 1 (The implementation of sustainability measures at major airports positively correlates with increased operational costs.) can be confirmed, as the data analysed in this study clearly illustrates that airports implementing significant sustainability measures often experience an initial rise in operational expenses showed with a lower EBITDA. For example, Amsterdam Airport and Istanbul Airport, both of which achieved some of the highest Airport Carbon Accreditation (ACA) levels, faced increased costs associated with implementing sustainability initiatives, such as upgrading infrastructure, adopting renewable energy solutions, and enhancing waste management systems. These high upfront investments in sustainability measures are necessary to meet high environmental goals and align with global sustainability standards.

Additionally, operational costs rise as airports incorporate new technologies, train personnel, and reorganize operations to support sustainability targets. This increase in expenditure often puts short-term pressure on financial metrics such as EBITDA, as seen with Amsterdam

Airport, which showed fluctuating efficiency scores before reaching optimal performance in 2023. Similarly, Istanbul Airport's operational costs have risen alongside its progressive sustainability efforts, as evidenced by its improving efficiency and EBITDA over time. These patterns support the idea that achieving high sustainability standards requires substantial financial costs, reinforcing the hypothesis that operational costs are positively correlated with sustainability investments.

However, while the short-term costs are significant, the study also shows that airports with consistent sustainability strategies, like Sydney and Changi Airports, can eventually offset these costs. Over time, cost-saving benefits from energy efficiency, optimized resource consumption, and improved reputation contribute to long-term profitability, validating the importance of these investments despite the initial financial burden. This reinforces the idea that while sustainability measures initially increase operational costs, they also set the foundation for enhanced financial and operational performance in the long term.

Hypothesis 2 (The recognition of sustainability as a strategic priority influences the financial commitment of airports to environmental measures.) can be confirmed, as the efficiency trends among the studied airports demonstrate that sustainability-oriented strategies significantly impact financial decisions and operational outcomes.

Amsterdam Airport is a key example of an airport that prioritizes sustainability. In 2018, its efficiency was slightly below optimal (0.973), likely reflecting the operational costs and resource allocation required for its environmental measures. By 2019, AMS achieved full efficiency, demonstrating the alignment of its sustainability initiatives with operational goals. However, its decline in efficiency to 0.943 in 2022 suggests the ongoing financial and operational challenges of maintaining high sustainability standards. The recovery to full efficiency in 2023 underscores the long-term payoff of sustained financial commitment to environmental priorities.

Istanbul Airport, which opened in 2019, exemplifies the ongoing benefits of strategic prioritization in sustainability. Starting with an efficiency score of 0.776 in 2019, IST improved consistently over the following years, reaching 0.979 in 2023. This upward trajectory reflects the airport's growing focus on sustainability as part of its operational strategy. Despite the initial costs associated with implementing sustainability measures, the airport's financial performance, particularly its EBITDA, has improved firmly, reinforcing the idea that prioritizing environmental goals can produce long-term financial and operational benefits.

Guarulhos Airport, on the other hand, provides a different case. With efficiency scores declining from 0.701 in 2018 to 0.429 in 2023, GRU highlights the challenges faced by airports that do not prioritize sustainability as a core strategy. The absence of significant environmental measures, as shown by its lack of ACA accreditation, correlates with inefficiencies in both financial and operational metrics. This underscores the importance of viewing sustainability not as a minor thing but as a strategic priority for long-term success.

Boston Logan International Airport represents a more variable case, showing fluctuations in efficiency scores. Despite achieving full efficiency in 2022, its score dropped to 0.873 in 2023. This variation reflects the challenges of balancing high sustainability investments with consistent financial performance. Nevertheless, BOS has demonstrated a commitment to sustainability, and its ability to reach full efficiency in certain years highlights the potential of aligning sustainability with strategic planning.

Hypothesis 3 (The regulation in the country on sustainability positively correlates with an increase of sustainability measures.) is validated by this study, as the data demonstrates a clear link between the regulatory frameworks of a country and the adoption of sustainability practices by its airports. Airports located in regions with stricter sustainability regulations, such as the European Union, consistently exhibited higher levels of compliance with environmental standards and stronger sustainability practices. This is evident in their higher Airport Carbon Accreditation (ACA) levels and their ability to integrate sustainability into their operations.

For instance, Amsterdam Airport, Barcelona Airport and Frankfurt Airport, both located in the European Union, consistently achieved high ACA levels throughout the years analysed, reflecting their alignment with EU regulations that mandate emissions reductions, energy efficiency, and waste management initiatives. The EU's regulatory framework requires airports to meet specific environmental goals, such as the reduction of greenhouse gas emissions under the European Green Deal. This regulatory pressure has incentivized airports like AMS, BCN and FRA to invest heavily in sustainability measures, ensuring they meet both national and EU-wide requirements.

In contrast, Guarulhos Airport in Brazil highlights the impact of weaker regulatory frameworks on sustainability adoption. Brazil's sustainability regulations in the aviation sector are less rigorous compared to those in the EU. This is evident in GRU's lack of ACA accreditation and its consistent inefficiency throughout the years analysed, with a significant decline in efficiency from 0.701 in 2018 to 0.429 in 2023. The absence of strong regulatory requirements appears to

have limited GRU's adoption of environmental measures, leaving the airport behind its global counterparts in terms of sustainability.

Another example of regulation driving sustainability can be seen in Istanbul Airport. Although Turkey is not part of the EU, the airport's efficiency has improved consistently from 2019 to 2023, partly due to the country's growing focus on aligning with international standards and its competitive desire to position IST as a leading global hub. The airport's gradual adoption of sustainability measures reflects the influence of regional and global regulatory pressures.

This study also highlights the role of regulations in incentivizing innovation. In regions with robust regulatory frameworks, airports are more likely to adopt advanced technologies and implement measures such as renewable energy projects, efficient waste management systems, and water recycling programs. For example, Changi Airport in Singapore, while not governed by EU regulations, operates in a region with strong national policies on sustainability. These policies have driven the airport to maintain high levels of operational efficiency while achieving significant environmental benchmarks.

Hypothesis 4 (The absence of sustainability measures will negatively impact airport business.) is strongly supported by this study. The data highlights that airports with insufficient sustainability measures consistently show inefficiencies in both operational and financial performance.

Guarulhos Airport, with its efficiency scores declining from 0.701 in 2018 to 0.429 in 2023, exemplifies the detrimental effects of neglecting sustainability measures. GRU lacks any Airport Carbon Accreditation (ACA), highlighting a minimal commitment to reducing emissions, optimizing energy, water consumption, and improving waste management practices. This absence of sustainability initiatives correlates with lower EBITDA and suboptimal passenger and aircraft movement metrics compared to other airports. GRU's inefficiencies, driven by the lack of environmental measures, have hindered its ability to align operational performance with global sustainability standards.

Efficient airports like Sydney, Singapore Changi, and Frankfurt further demonstrate the advantages of embedding sustainability as a strategic priority. These airports maintained full efficiency across all years analysed, reflecting the operational and financial benefits of constant environmental initiatives. Sydney Airport, with its ACA level 3 accreditation, exemplifies how moderate but well-planned sustainability investments can yield consistent profitability and efficiency.

5. CONCLUSIONS

5.1 MAIN IDEAS

This study looked at how sustainability and financial performance are connected in large airports, focusing on their development into aerotropolises. Using Data Envelopment Analysis (DEA) on ten airports over several years, the study showed that sustainability efforts have a strong impact on how efficiently airports operate and how well they perform financially. Airports in places with stricter environmental rules were often more efficient, showing how important clear and consistent policies are.

The study also included a SWOT analysis of less efficient airports to better understand their strengths, weaknesses, opportunities, and threats. Strengths like modern infrastructure and existing green programs were compared to weaknesses such as high costs and poor resource use. Opportunities, like new technologies and rising interest in green practices, were noted alongside threats like economic challenges and uneven regulations. Together, these methods gave useful ideas for improving airport efficiency while focusing on sustainability.

The results highlighted the challenge airports face in balancing the high upfront costs of being more sustainable with the long-term benefits, such as better reputation, stronger stakeholder trust, and improved operations. Airports that do not prioritize sustainability risk losing their competitive edge and customer confidence. This study shows how important it is for airports to make sustainability a core part of their strategy to succeed both financially and environmentally.

5.2 SPECIFIC OBJECTIVES EVALUATION

Here we will be looking at the 5 specific objectives defined in order to evaluate them.

1. How sustainability measures impact profitability

Sustainability initiatives often require significant upfront investments, which can strain financial resources in the short term. However, over time, these measures lead to benefits such as stronger brand reputation, improved passenger satisfaction, and better compliance with regulations. On the long-run airports also become efficient as per the study, supporting the idea that sustainability is a long-term investment with positive financial outcomes.

2. Examine the effect of country regulation on airports' implementation of sustainability measures

Regulations play a critical role in encouraging airports to adopt sustainability measures. Airports located in countries with strict environmental policies tend to excel in sustainable practices. This underscores how regulatory frameworks can act as a powerful driver for progress and innovation in the aviation industry.

3. Investigate the reasons for the non-adoption of sustainable practices

Some airports face significant challenges in adopting sustainability measures. High initial costs, limited funding, and a lack of stakeholder alignment are common barriers. Airports in developing countries, in particular, struggle with resource and financial constraints, making it harder for them to prioritize sustainability.

4. Analyse the business implications of airports not adopting sustainable measures

Airports that neglect sustainability face risks such as reputational damage, reduced partnerships with airlines and stakeholders, and possible penalties. Additionally, these airports may lose their competitive edge as sustainability becomes a key factor in global airport performance evaluations or the resources becoming more expensive putting profit at risk.

5.Identify airports' successful strategies in sustainability

Successful airports use various strategies, including renewable energy adoption, water conservation and effective waste management reducing direct emissions. These strategies not only improve environmental performance but also enhance operational and financial efficiency.

To sum up, all the specific objectives were achieved with this study.

5.3 GENERAL OBJECTIVE DISCUSSION

The main goal of assessing sustainable aerotropolis viability was explored from different angles. The findings show that sustainability measures are crucial for improving airports' economic performance and efficiency. As more countries adopt this model, balancing economic growth with environmental care becomes even more important. The study concludes it is possible for aerotropolis to be sustainable as major airports such as Changi are sustainable and fully efficient although it is important to keep in mind that a lot of can factors influence this possibility such as financial constraints. This shows that our general objective was achieved.

5.4 CRITICAL REFLECTION AND ANALYSIS

This study shows that sustainability is essential for the aerotropolis model, but it comes with challenges. Airports often face financial pressure in the short term because of the high costs of

green initiatives. However, these efforts pay off in the long run by improving reputation, trust, and efficiency.

One key finding is that airports in regions with stricter rules tend to perform better in sustainability. This shows how important consistent global policies are to encourage more airports to adopt sustainable practices. Global carbon standards, incentives for green technology, and stricter reporting requirements could help make these practices more common.

Sustainability can seem like a financial burden at first, but it often leads to innovation. Airports that include sustainability in their planning often find ways to reduce waste, save resources, and create new services. Over time, these benefits can balance out the initial costs and even improve financial performance.

Another important point is the role of stakeholder involvement. Airlines, passengers, and local communities increasingly expect airports to be environmentally responsible. Meeting these expectations can strengthen relationships and help airports stay competitive. Airports should work with stakeholders to find solutions that meet both environmental and operational goals.

Technology also plays a big part in making airports more sustainable. New systems for renewable energy, digital tools, and better resource management can help airports reduce their environmental impact and stay efficient. Airports that lead in using these technologies often set examples for others to follow.

In summary, while adopting sustainability is challenging, it is a necessary step for the future of the aviation industry. The key is to balance environmental goals with financial needs, supported by clear rules, stakeholder collaboration, and innovative technology. This approach will help airports stay resilient and lead the way to a more sustainable future.

5.5 LIMITATIONS

This study has some limitations:

- The DEA model depends on the quality of data, which may not fully capture all aspects of airport operations.
- Some of the data was predicted so it might not be reliable.
- The way airports report their data is not always the same but it might seem it is which can affect study results.

- Focusing on specific years and airports may limit how broadly the findings can be applied.
- External factors like economic conditions and COVID-19 add complexity to the analysis.

5.6 FUTURE RESEARCH

Future studies could delve deeper into understanding the long-term financial impacts of sustainability measures on airport operations. While this study provides insights into the relationship between sustainability and financial outcomes, future research could focus on identifying the exact timeline for return on investment (ROI) for green initiatives. Understanding when investments in renewable energy, waste management, and carbon offset programs begin to generate cost savings could provide airports with a clearer roadmap for prioritizing their sustainability goals.

Another promising area for exploration is the study of smaller airports. Smaller airports often face unique challenges, such as limited budgets, fewer resources, and lower passenger volumes, which make sustainability efforts particularly difficult. Future research could identify tailored solutions for these airports, exploring innovative funding mechanisms, scalable technologies, and regional collaborations that enable them to overcome their barriers to sustainability.

Additionally, a comparative analysis of airports across regions with differing regulatory environments could yield valuable insights. For instance, investigating how airports in regions with weaker environmental regulations can still achieve sustainability goals despite limited external pressure could reveal effective strategies for global adoption. This could include partnerships with airlines, stakeholder engagement, and voluntary sustainability programs that go beyond compliance.

Exploring technological innovations is another avenue for future research. The role of artificial intelligence (AI), Internet of Things (IoT), and digital platforms in optimizing airport efficiency and sustainability remains underexplored. Studies could investigate how smart technologies can revolutionize resource management, energy consumption, and passenger services while reducing the environmental footprint of airports.

Finally, future research could examine the role of collaboration between airports, airlines, and governments in achieving shared sustainability goals. Multi-stakeholder approaches, such as co-financing green initiatives or setting industry-wide standards, could be evaluated for their

effectiveness in driving sustainable practices at a larger scale. These studies could offer a blueprint for global efforts to transform aviation into a more sustainable industry.

5.7 FINAL REFLECTION

This study highlights the essential role of sustainability in shaping the future of the aerotropolis model. As the aviation industry continues to grow, airports must strike a balance between being economic drivers and minimizing their environmental impact. The study reveals that while challenges such as high upfront costs, uneven regulations, and operational hurdles exist, sustainability is not only possible but crucial for long-term success.

The integration of the SWOT analysis provided deeper insights into these challenges and opportunities. Strengths such as advanced infrastructure and existing sustainability programs give airports a solid foundation, while weaknesses like resource inefficiencies and financial strain highlight areas needing improvement. Opportunities such as advancements in green technology and increasing demand for eco-friendly practices present clear paths forward, though threats like regulatory gaps and economic pressures remind us of the complexity of this transition.

The research underscores that airports adopting sustainability as a core strategy are better equipped to adapt to global shifts, attract environmentally conscious stakeholders, and remain competitive. Although financial strain may be a short-term issue, the long-term benefits—enhanced efficiency, cost savings, improved reputation, and regulatory compliance—clearly outweigh initial investments. The importance of consistent global policies also emerges as a key finding; airports in regions with strict regulations, such as the European Union, perform better, highlighting the need for harmonized standards worldwide.

However, achieving sustainability goes beyond regulations. It requires strong commitment, innovative thinking, and collaboration among airports, airlines, and governments. The potential for aerotropolises to serve as global examples of sustainable development is immense. By adopting cutting-edge technologies, fostering regional cooperation, and prioritizing sustainability, aerotropolises can transform how cities grow around airports, creating ecosystems that are economically vibrant and environmentally sustainable.

As the aviation industry evolves, its approach to sustainability must evolve as well. A focus on integrating financial, operational, and environmental goals through innovation and collaboration is vital. This thesis contributes to ongoing discussions on sustainable aviation and provides a framework for future research, policy-making, and practical applications in the

aerotropolis model. Airports that embrace these changes will not only thrive in a competitive market but also play a critical role in combating climate change and fostering sustainable global development.

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APPENDIX 1 – AIRPORT DATA SOURCES

Josep Tarradellas Barcelona–El Prat Airport	Annual Reports: https://www.aena.es/en/shareholders-and-investors/financial-and-economical-information/financial-and-operational-publications.html?anio=2023#annualreports Sustainability Reports: https://www.google.com/url?q=https://www.aena.es/en/corporative/about-aena/annual-reports.html&sa=D&source=editors&ust=1733152980514897&usg=AOvVaw33ujNcQPgwJeE2qKGKz-hU
Amsterdam Airport Schiphol	Annual Reports: https://www.schiphol.nl/en/schiphol-group/archive-annual-reports/
Frankfurt am Main Airport	Annual Reports: https://annual-report.fraport.com/annual-report/2023/en/
İstanbul Havalimanı Airport	Sustainability Reports: https://www.google.com/url?q=https://www.igairport.aero/en/sustainability/green-library/&sa=D&source=editors&ust=1733134380371335&usg=AOvVaw3MBGmwFpnH-Bnb7XlZiNfI
Hong Kong International Airport	Annual Reports: https://www.hongkongairport.com/en/airport-authority/publications/annual-interim-reports/ Sustainability Reports: https://www.hongkongairport.com/en/sustainability/sustainability-report.page
Tokyo International Airport	Annual Reports: https://www.tokyo-airport-bldg.co.jp/en/ir/library/index.html Sustainability Reports: https://www.tokyo-airport-bldg.co.jp/en/sustainability/library/
Singapore Changi Airport	Annual Reports: https://www.changiairport.com/en/corporate/our-media-hub/publications/reports.html Sustainability Reports: https://www.changiairport.com/en/corporate/our-sustainability-efforts/environment.html#tabs-ccc1a2c6dc-item-ad4623c5bc-tab
Kingsford Smith International Airport	Annual Reports: https://www.sydneyairport.com.au/investor/investors-centre/reports/index.html Sustainability Reports: https://www.sydneyairport.com.au/corporate/sustainability/annual-performance
Boston Logan International Airport	Annual Reports: https://www.massport.com/business/finance/annual-comprehensive-financial-report Sustainability Reports: https://www.massport.com/environment/project-environmental-filings/boston-logan
Governador André Franco Montoro International Airport	Annual Reports: https://ri.gru.com.br/informacoes-aos-investidores/informacoes-financeiras/ Sustainability Reports: https://ri.invepar.com.br/en/sustainability-reports/
Airport Carbon Accreditation	https://www.airportcarbonaccreditation.org/accredited-airports/

APPENDIX 2 –DATA COLLECTION TABLE

				Inputs				Outputs			
		DMUs	Airport Code	Direct Emissions (tCO2e)	Total Electricity Consumption (kWh)	Total Waste Generated (metric tons)	Water Consumption (m³)	EBITDA (M)	Nº PAXs (M)	Aircrafts Movement (K)	ACA Level
Europe	2018	Barcelona Airport	BCN	4293.43	200160000.00	19851.66	1036674.00	478.19	50.20	335.70	2.00
	2019			4020.89	203040000.00	25695.72	1007244.00	497.92	52.70	345.00	2.00
	2022			3795.80	228420000.00	7087.86	6439140.00	374.20	41.60	283.00	3.00
	2023			3128.57	233820000.00	7407.52	6673620.00	544.07	49.90	319.00	3.00
Europe	2018	Schiphol Airport	AMS	20339.00	200000000.00	16621.47	1289383.75	552.45	70.96	517.73	3.50
	2019			19037.00	198000000.00	16612.09	1549323.60	599.43	71.68	515.81	3.50
	2022			11616.24	194040000.00	11365.64	1574421.24	155.73	52.47	422.30	3.50
	2023			9828.39	188218800.00	17295.00	1335222.53	304.50	61.89	464.72	4.50
Asia	2018	Istambul Airport	IST	-	-	-	-	-	-	-	-
	2019			37371.00	178998372.00	26727.19	1331673.00	513.01	52.92	325.00	0.00
	2022			27199.00	234167578.00	43507.00	1330820.00	783.54	64.28	329.90	1.00
	2023			19611.00	232798953.00	53135.00	1492193.00	894.40	76.03	505.97	3.00
Asia	2018	Changi Airport	SIN	1406.00	456100000.00	16700.00	3226000.00	973.01	66.30	386.00	3.00
	2019			1360.00	449600000.00	16200.00	3272000.00	1042.20	62.90	363.00	3.00
	2022			966.00	342300000.00	9500.00	2415000.00	518.58	42.60	257.00	3.00
	2023			1207.80	389000000.00	16400.00	2028600.00	827.49	62.90	344.00	3.00
Europe	2018	Frankfurt Airport	FRA	3244.45	528138337.56	16396.60	1271940.00	654.82	70.00	511.86	3.00
	2019			2929.33	521726115.28	16361.80	1525980.00	684.40	70.60	513.91	3.00
	2022			1947.02	478957202.40	10614.00	1470300.00	597.28	49.00	382.21	3.00
	2023			2020.66	491154440.00	16588.00	1280640.00	698.32	59.36	430.44	3.00
Asia	2018	Haneda Airport	HND	17270.50	163485454.97	12267.00	898486.14	390.46	84.89	87.90	0.00
	2019			17359.20	164325125.82	10750.00	903100.82	316.35	85.33	85.80	0.00
	2022			14967.00	152525000.00	6115.00	701698.00	126.50	80.22	47.80	0.00
	2023			19194.00	169916000.00	9118.00	1082124.00	353.37	87.12	103.40	0.00
Oceania	2018	Sydney Airport	SYD	5569.00	124343056.00	6489.00	617891.00	789.43	44.40	344.15	3.00
	2019			5755.00	124040000.00	6360.00	705702.00	718.47	44.40	324.10	3.00
	2022			6603.00	94110000.00	4273.00	590930.00	471.80	29.12	252.40	3.00
	2023			6508.00	126691389.00	5830.00	628496.00	736.08	38.60	297.00	3.00
America do Norte	2018	Boston Logan Airport	BOS	47493.00	151682956.00	10613.53	885195.00	341.06	39.50	412.16	0.00
	2019			51359.00	169634586.05	10734.20	915504.53	380.64	41.90	426.51	0.00
	2022			31415.00	250484024.43	12840.10	627255.90	429.18	31.10	341.98	0.00
	2023			30001.33	282200988.98	13113.99	768663.00	475.30	39.20	396.54	1.00
Asia	2018	Hong Kong Airport	HKG	10110.00	299760000.00	25410.00	458492.00	1442.62	75.10	429.00	3.00
	2019			11050.00	306785000.00	21499.00	434682.00	1078.02	60.90	377.00	3.00
	2022			4180.00	243337000.00	5038.00	221432.00	94.97	12.40	161.00	3.00
	2023			1915.35	280008000.00	13675.00	308742.00	639.94	45.20	310.00	4.00
America do Sul	2018	Guarulhos Airport	GRU	22572.00	162151000.00	11346.00	1038055.00	297.12	42.23	291.99	0.00
	2019			22643.00	174088000.00	11016.00	1037971.00	307.25	43.00	293.92	0.00
	2022			28269.98	277868130.00	14243.84	1801957.00	397.48	34.50	242.90	0.00
	2023			28358.88	297318899.10	13816.52	1801812.84	397.88	41.30	274.92	0.00