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Sustainable airport development: a financial modelling and simulation approach for scenario-based decision making

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Abstract

The green transformation of the aviation sector requires significant investments from airports into new infrastructure or changes in energy supply facilities (e.g. hydrogen infrastructure). Understanding the economic implications of these investments across different airport sizes and market conditions is critical for airport operators and other stakeholders such as airlines, regulators, and public entities. However, existing financial reporting standards do not provide sufficient guidance for airports undergoing the sustainability transition. Previous studies predominantly focus either on evaluating environmental sustainability aspects or on the assessment of investment decisions, but rarely integrate both perspectives. This study addresses this gap by developing an adaptable financial modelling framework that assesses the impact of sustainability investments of airports. It focuses on the economic implications and includes emission calculations (within a linked extension of the model) to examine the interdependencies between economic and environmental sustainability. The simulation-based approach enables the consideration of various developments and existing uncertainties, thereby providing the structure for an analysis that demonstrates the impact of these investments. The implementation of the framework is demonstrated by providing examples of potential scenario analyses. Financial statements and key performance indicators (KPIs) are derived and analysed to assess the model's applicability. The results aim to support airport operators in making informed investment decisions that balance financial viability with sustainability goals.

Keywords: Airport Development, Sustainability, Financial Modelling, Technology Asessment

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1. Introduction

In a globalised world, air transport is crucial for providing connectivity between continents, countries and regions. Airports play a key role in this environment, serving not only as gateways for seamless connectivity but also as vital hubs, facilitating the integration of diverse economies and fostering meaningful human connections. (Chourasia et al. 2021) An intricate tension field for airports arises from the need to serve an increasing number of passengers on the one hand and the ambitious goals to reduce their environmental impact on the other hand. This requires a substantial transformation of the airports. (Monsalud et al. 2015) Airports need to cope with the challenges and opportunities that are involved in harmonising the increasing demands of air travel with the urgent need to become sustainable facilitators of global connectivity and economic exchange. (Di Vaio and Varriale 2020)

One key challenge for airports is the development of their infrastructure to provide new energy carriers for low-carbon aviation. This may include the installation of hydrogen refuelling systems or charging terminals for electric aircraft. At the same time, the airport's own energy supply must become more sustainable. Increased use of renewable energy, intelligent energy storage solutions, and efficient resource management will be essential for reducing the airport's carbon footprint. Additionally, airports must expand to accommodate the growing demand for air travel while minimising their environmental impact. Through forward-thinking planning and sustainable development, airports can effectively balance growth with environmental responsibility.

This sustainability transformation has substantial financial implications for the airports. Although these implications are important for the long-term success of airports, they have not been explored adequately in the literature. While well-established and topical literature exists on airport benchmarking, such as the annual ATRS Airport Benchmarking Report (2022) and the Airport Performance Measures by Airport Council International (ACI) (2012), less attention is given to bottom-up airport financial modelling. A first approach towards financial modelling was provided by Koch (2006), but it does not focus on the strategic development of airport systems and the specific decision-making principles involved in sustainable airport development projects, despite the considerable investments. Weiss (2020) provides a socio-economic analysis of the current airport situation but does not consider a scenario-specific approach. Thus, the models do not draw the connection between financial assessment and sustainable development scenarios.

The objective of this paper is to address the research gap concerning the financial implications of sustainability transformations at airports. Strategic decision-making for airport transformations requires in-depth assessments of the potential impacts of future investments rather than comparing airports through benchmarks. We seek to contribute to this important research field by developing a simulation model that allows to analyse the financial implications of different sustainability transformation scenarios for airports. In particular, we present the overall concept of the simulation model and discuss the individual blocks of the model as well as their interactions in detail. They describe the airport's cash flows using financial calculations and key performance indicators (KPIs). Exemplary implementation steps based on a potential case study are provided, forming the basis for a scenario-specific analysis.

The study is conducted within the project 'THOR: Towards Zero Emission Airports' at the German Aerospace Center (DLR) in cooperation with Hamburg Airport, a German airport. The project scope is to analyse possible ways to achieve zero carbon and energy-efficient airport operations, to which European airports have committed themselves by 2050 due to Airport Council International (ACI).

2. Overall model concept

To capture the complex interactions within sustainable airport development, we develop a model that enables the simulation of different scenarios. Model requirements arising from real-world planning problems include the estimation of the financial impact on cash in- and outflows, the determination of when and in what form to invest in infrastructure, addressing how to manage 'uncertain' technologies in a decision-support setting, and understanding the environmental impact of infrastructure and process changes.

The financial airport model comprises the main financial reports as well as the most important drivers for cash in- and outflows. It is implemented in Python. The model describes the multi-year financial airport development depending on surrounding conditions and specific airport decisions. Fig. 1 shows the structure of the financial model containing relevant input data, calculations, and resulting financial statements.

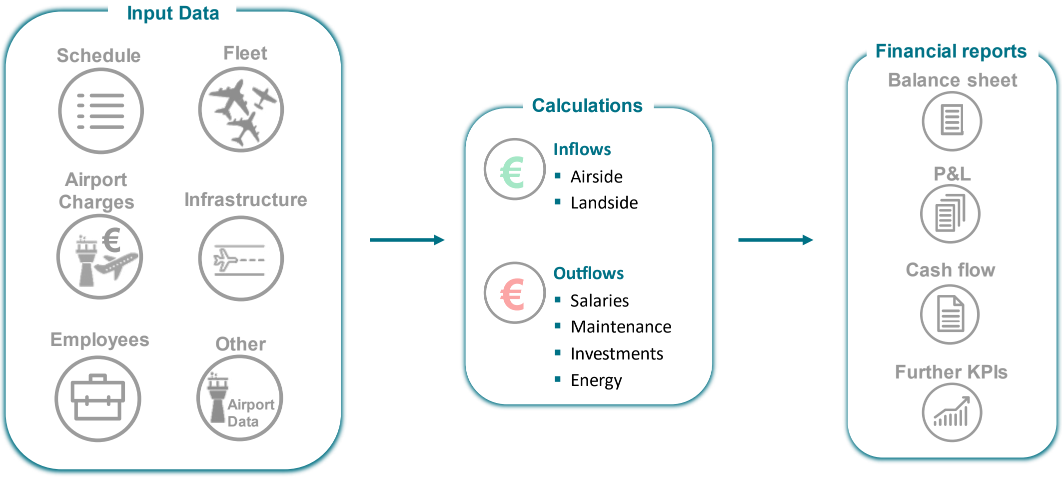

Fig. 1. Structure of the financial airport model

The following sections outline the structure and key components of the model. As depicted in Fig. 1, the model is based on various airport-specific **input data**. The next step is the **calculation of cash in- and outflows** belonging to the airport operator's business model. The result of these calculations are the **financial statements** that summarise the economic performance of the airport.

2.1. Input data (model parameters)

Examples of input data from the THOR project are the estimated traffic forecasts until 2050 and the associated fleet of conventional and innovative aircraft. The related changes, as well as changes in airport infrastructure and processes, result in an economic change that can be observed through the calculated financial statements.

Flight traffic, which forms the basis of the model, consists of flight schedules covering two exemplary weeks (summer and winter) for each 5-year period between 2025 and 2050. The given flight schedules show the expected increase in the passenger volume within the upcoming decades. In general, the model can work with various flight schedules, as it transfers the day-based flight schedule to a schedule on an adjustable time frame. The financial statements are preferably calculated on a yearly basis. The resulting schedule is based on a date-time object so that cash in- and outflows can be put as time-based 'price tags' to match, for example, the aircraft belonging to the fleet that is in use within the specific time frame.

Aircraft fleet describes the type of aircraft that arrive at and depart from an airport. In contrast to the past, not only new aircraft models evolve, but also new propulsion technologies will be deployed in future aircraft fleets. The fleet used in the model depicts this change within the provided flight schedules. The aircraft are assigned to the routes in the flight schedule based on their seat class. To calculate the expected increased volume of passengers (pax) travelling on a flight, a seat load factor is linked to the fleet.

Existing and future infrastructure and related investments are needed to calculate expenses for maintenance and the cash flow of the airport. This information could be collected through various meetings and workshops with the airport as well as (annual) statements of the airport, supplemented by further assumptions where necessary. The existing infrastructure sets the basis for the current capacity of the airport and the layout that is needed for modelling aircraft movements on the airside and the passenger journey on the landside.

Potential infrastructure investments to meet the airport's energy demand can include wind turbines, photovoltaic (PV) systems, and battery storage. Additional investments may focus on supplying energy to aircraft and ground handling operations, such as hydrogen storage and distribution systems as well as electric charging infrastructure.

The timing and magnitude of these investments are critical factors influencing their feasibility and integration into the overall airport energy system. All necessary investments are documented within an investment schedule, which details both the financial volume and the temporal distribution of expenditures. Since large-scale investments are rarely completed within a single year, the associated capital expenditures are spread over multiple years before and after the installation is completed. For example, the development of a wind park comprising six turbines, with a total investment of approximately €70 million, can significantly contribute to the airport's electricity supply. (Hamburg Airport 2025) This investment may include the acquisition of land and the phased installation of individual turbines over a period of several years. Similarly, the implementation of hydrogen infrastructure, such as storage tanks for liquid hydrogen, requires substantial financial resources, with total investments potentially reaching a three-digit million-euro range, depending on the scale and stage of infrastructure development. (Gronau et al. 2023) The information on these investments can be sourced from the airport operator, potential technology providers, or research institutes. The potential changes of investment volumes for specific new technologies due to technological development, learning curves and economies of scale are considered if available.

Airport charges are fees that airlines pay to the airport operator for using the airport's infrastructure and services. They include, for example, landing, take-off, passenger-, and handling fees, which vary across airports, aircraft types, and numbers of passengers. These charges are an essential source of cash inflow for airports that help cover operational expenses and to finance infrastructure investments. Besides airport charges, there are also taxes and levies that are collected within the same process. However, these cash flows only represent a transitory item and are not considered for the airport operator's business model. Airport charges can also be subject to (governmental) regulations by changing or implementing specific charges (for example, to foster sustainable aircraft types). Further details on specific charges are discussed in Section 3.

3. Financial calculations, resulting KPIs and data requirements

The airport cash flows can be divided into cash in- and outflows. The cash inflows can be divided into an aeronautical and non-aeronautical part (Fig. 2). The aeronautical cash inflows consist of airport charges. The non-aeronautical cash inflow mainly consists of retail concessions and parking, although there may be other cash flow sources based on the airport's business model. Cash outflows can be divided into operational and capital expenses. The main input parameters to calculate these are aircraft-, passenger- or infrastructure-specific. The airport charges are modelled in Python and saved within a data frame that links all cash flows to the specific aircraft so that the model depicts the information like a price tag with the exact date and time (if feasible) for the specific aircraft. Thus, the model can be used to run short- and long-term analyses by selecting the corresponding timeframe.

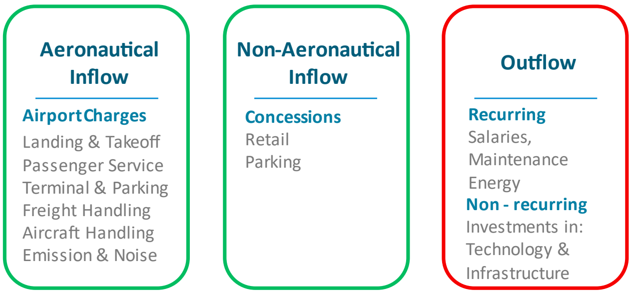

Fig. 2. Airport cash flow

3.1. (Non-)Aeronautic cash inflows

Aeronautical cash inflows mainly consist of airport charges published by the airport. They are mainly based on the number of passengers travelling with an aircraft or other aircraft-related units like the maximum take-off mass (MTOM). Passenger-related charges such as the passenger charge or the PRM charge (Passenger with Reduced Mobility) mainly focus on passenger handling and linked baggage-handling processes. Aircraft-related charges cover take-off and landing, the parking of the aircraft, as well as related (noise) emissions. However, some charges are also based on units like daytime, turnaround duration, or aircraft emissions (NO_x, HC). Besides airport charges, governmental taxes and levies are calculated but not considered as a part of the airport's cash inflow. The charges are calculated for every turnaround of an aircraft, based on the corresponding airport charge and its calculation factor. It is saved in a data frame linked to the flight schedule. The base year for the calculation of aeronautical cash flows is 2025. Charges for the upcoming decades do not only take inflation into account but can also depict changes in regulations (e.g. prioritising aircraft with sustainable fuels).

Non-aeronautical cash inflows are generated from activities that are not directly linked to the airport's core operations. These cash flows are typically calculated in relation to the airport's workload units, measured primarily by passenger numbers. However, they are also influenced by passenger behaviour, including choice of transport mode for landside arrival to and departure from the airport, as well as the average time spent within the terminal. The key drivers in this category are retail concessions and parking fees, which are estimated as described next.

Retail concessions are calculated based on the airport's traffic performance and the average length of stay in the terminal. The relevant parameters are derived from a statistical survey conducted at Hamburg Airport, as mentioned by Weiss (2020). The formula below can be used to calculate the retail concessions and includes social factors (e.g., purchasing, arrival, and movement behaviour) alongside airport-specific characteristics (such as system architecture in the economic balance) through the input variables.

$$Retail_{Concessions} = \gamma_{\%} * \sum_{k=1}^{2} \alpha_k * PAX_k * T_k * \beta_k * (1+i)^{(y-2025)} \quad (1)$$

$\gamma_{\%}$: *Turnover rent* | α_k: *Share of travel mode* | PAX_k: *Departing Passengers* | T_k: *Available time for consumption*
β_k: *Spendings per minute* | $k = 1$: *Scheduled*, $k = 2$: *Charter* | i: *Inflation rate* | y: *Year of observation*

The formula is based on the total number of departing passengers and provides the proportion of passengers consuming at the airport. By considering the available time passengers have in the terminal and their mode of travel (either charter or scheduled flight), the potential concessions can be estimated. Since the airport does not receive the full cash flow generated by retail activities but rather a rental income based on turnover, a rent factor is applied to the turnover to determine the airport's share.

Parking fees are determined using the airport's traffic performance and based on the following formula that provides an initial approximation for parking concessions. To do so, the average parking events are estimated, including their duration of stay, and linked with Hamburg Airport's parking fee schedule. (Weiss 2020)

$$Parking_{Concessions} = PAX_{Departing} * Cars_{Share} * Duration * Fee * (1+i)^{(y-2025)} \quad (2)$$

$PAX_{Departing}$: *Departing Passengers* | $Cars_{Share}$: *Propotion of PAX travelling by car*
Duration: *Average length of stay* | *Fee*: *Average parking fee* | i: *Inflation rate* | y: *Year of observation*

For both departing and arriving passengers, distinct average values are calculated from parking duration data collected at Hamburg Airport, covering stays from under 30 minutes to long-term parking of up to two weeks. The resulting cash flow from parking for departing and arriving passengers is then determined by multiplying the passenger count by the respective car usage share and the calculated parking fees.

3.2. Cash outflows

Airports incur both **recurring and non-recurring cash outflows** to maintain operations and to expand infrastructure. Recurring outflows include salaries as well as ongoing maintenance expenses for runways, terminals, and equipment.

Non-recurring cash outflows in airport operations include large one-time capital expenditures and investments, such as investments into energy (supply) infrastructure or new terminal buildings. These long-term projects require significant capital but are essential for accommodating increasing passenger demand and improving efficiency. Due to their irregular nature, these cash flows require special planning and separate treatment in financial analyses to accurately reflect the airport's overall cost structure. These investments are based on the historic and future investments planned at the airport. To model the impact of a potential development scenario, existing and potential investments are considered in a list of investments as shown in Table 1.

Table 1. List of investments (exemplary investments and figures)

Project description	EIS	EOL	Volume [Mio €]	Investment distribution around EIS					
				-2	-1	0	1	2	[Years]
Wind Park	2030	2070	70	10	25	40	15	10	**[%]**
Battery	2035	2070	60	5	20	50	15	10	**[%]**
LH_2 storage tank	2040	2070	100	10	20	50	15	5	**[%]**

The exemplary table contains the project description, for example, an investment named 'LH_2 storage tank' with its entry into service (EIS), its approximate end-of-life (EOL), and the investment volume. The investment is distributed into the year of its entry into service as well as the years before and after it as percentages of the investment volume. The distribution for large investments, for example, is caused by preparatory feasibility studies, land acquisition, installation, project completion, and follow-up work.

Recurring cash outflows mainly include expenses for energy, salaries, and annual maintenance.

Salaries are recurring and based on the airport traffic performance in terms of passengers (pax) using a regression function that is derived by Weiss (2020) for European airports. The function shows a good approximation on employees. However, as the function is based on data until 2013, a validation, especially on effects due to the COVID-19 gap, is necessary to update and improve the accuracy of the function. The number of direct employees of an airport operator can be calculated as a function of passenger volume (PAX) and productivity changes over time.

$$Employees = (4{,}5 * PAX^2 + 519{,}3 * PAX) * (1 - \Delta P)^{a-2013} \quad (3)$$

ΔP: $Productivity\ increase\ in\ \%$ | a: $Year\ of\ observation$ | PAX: $Number\ of\ passengers$

The productivity factor is adjusted annually, using a defined rate of increase. The distribution of these employees across different operational sectors like airfield, terminal, support, and handling are also taken into consideration. The salary structure is considered by distributing employees into categories such as ground handling, engineering, administration, and management, with respective hourly rates and escalation factors. An escalation rate is applied to account for salary increases from a base year. This function provides a first estimation of airport salaries relating to traffic and operational productivity changes.

Annual maintenance expenses are calculated as a percentage of the investment volume, directly linking these expenses to the acquisition of the investment objects. This approach is used, as larger investments require higher maintenance efforts. A specific percentage of the investment volume is calculated for maintenance, with adjustments over time to reflect factors such as learning effects and wear and tear (Table 2). These adjustments are assumed to change in five-year intervals during the first 20 years of the asset's operational life, after which a fixed percentage is applied from the 21st year onwards.

Table 2. Estimation of maintenance costs

Year after EIS	1-5	6-10	11-15	16-20	>20
Approx. of maintenance expenses as share of investment	2,5%	3%	4%	4,5%	5%

3.3. Calculation of emissions

The emission calculation is based on the Airport Carbon Accreditation (ACA) of the Airport Council International (ACI). The CO_2 emissions are calculated within an adjacent model as part of the THOR project and are classified according to scopes 1 to 3. Non-CO_2 emissions are reported as CO_2 equivalents. The calculation is performed in a manner analogous to economic calculations, with the main influencing factors being the energy and fuel flows as well as one-time emissions resulting from investments in infrastructure and technology. The results of the emission calculation are used to compute key performance indicators in reference to the economic values.

3.4. Output data (financial statements & KPIs)

The model generates financial statements that include all relevant cash flows, providing an overview of the main drivers and highlighting their contributions to overall cash flows. In addition, key performance indicators (KPIs) link financial metrics with emission values. These KPIs can be based on aeronautical variables, such as **CO_2 emissions per movement or per passenger**, or on financial aspects, such as **emissions per unit of cash flow**.

The derived cash flows are then used to calculate the **Net Present Value** (NPV) by discounting all future cash flows arising directly from operations and capital expenditures. In order to estimate all relevant cash flows for the NPV, the time period before and after the analysed time frame has to be considered. The initial investments in design and construction are taken in order to calculate initial cash flows.

Instead of focusing on absolute values, the model provides the relative deviations of these metrics compared to a reference system. This approach facilitates the precise identification of the optimal timing for necessary actions – such as investments in new systems or adjustments to levies. To further explore the implications of these investments, additional methods such as real option analysis or Monte Carlo analysis can be utilised. These methodologies emphasise the uncertainties, irreversibility, and flexibility that accompany the evolving technological changes at airports.

4. Model deployment and scenario generation

The modelling framework has to be implemented with boundary conditions of an airport to be analysed. The **input data** described in the previous sections, for example, can be integrated into the model using Hamburg Airport as a case study. This data (e.g., list of airport charges, traffic forecast, infrastructure) can be sourced from the airport's published financial statements, as well as through interviews, workshops conducted in collaboration with the airport, and relevant literature. The timeframe to be analysed, based on the THOR case study, takes the years between 2025 and 2050 into account. However, to depict the current financial status of the airport and to verify the airport model, information about the past years is crucial. Thus, all relevant kinds of information, such as investments or relevant changes to the airport’s (financial) structure or processes, are collected and implemented into the initial model. As an example, all investments in the design and construction of the airport before the official opening are summed up to calculate an initial investment. Thus, a reference scenario can be implemented with the initial boundary conditions and without any changes of processes or infrastructure. This reference scenario can be compared with all potential scenarios and individual development measures.

After developing the initial model, potential scenarios can be implemented and analysed by defining specific airport development scenarios and changing the boundary conditions accordingly. Two potential airport development scenarios, a baseline and a sustainable airport scenario, are derived from the THOR project. Both scenarios depict Hamburg Airport, which has to manage a projected increase in passenger volume. Depending on the chosen development path, corresponding changes in processes and infrastructure are implemented to meet future demand.

Within the **baseline scenario**, which depicts the airport as initially implemented into the model, there are no major changes to the existing infrastructure and processes. The energy system remains the same based on the currently installed technologies as of 2025. No changes in infrastructure or processes are implemented to handle upcoming changes in aircraft designs or propulsion technologies. The baseline scenario serves as a benchmark against which all changes of a further airport development scenario can be compared to.

The **sustainable airport scenario** introduces modifications towards an upgraded energy (supply) system. This scenario includes investments into technologies such as a wind park providing electrical energy, chillers and batteries, and investments into the infrastructure to supply hydrogen and electric energy. Beyond mere energy system modifications, this scenario requires significant investments in technologies such as on-site storage for gaseous and liquid hydrogen, LH2 liquefiers, and charging facilities for electric aircraft and ground vehicles. The timeline and investment volumes of the implemented infrastructure are estimated.

Taking the baseline scenario (reference) and comparing it to the sustainable airport scenario, the differences can be quantified and outlined through the resulting financial statements. The NPV is then derived by discounting all future cash flows arising directly from operations and capital expenditures of the case study airport. The KPIs are provided based on this information and the emission calculation. The results can be compared graphically to illustrate the differences at first glance. An exemplary in- and output for a sustainable scenario is shown in Fig. 3, depicting the fleet mix of the sustainable scenario (input) and the resulting cash flows (output).

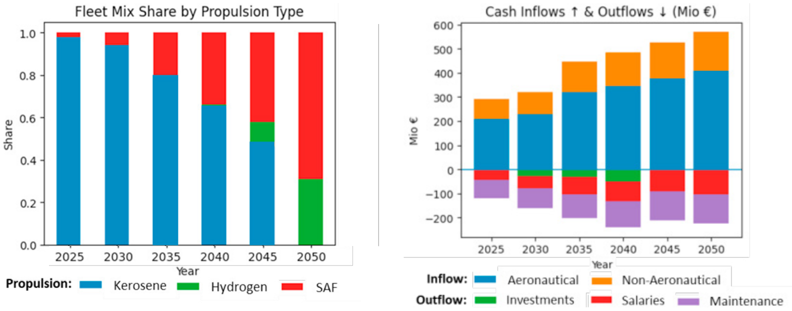

Fig. 3. Exemplary input: fleet mix (left) and output: cash flows (right)

Besides the analysis of different scenarios, a sensitivity analysis has to be carried out to assess how variations in factors such as investment volumes and timing impact cash flows.

5. Conclusion and outlook

This paper contributes to the field by developing a financial model for airports that fills the gap in the existing literature between financial assessment and sustainable airport development. The provided framework enhances the understanding of an airport's financial structure by presenting relevant boundary conditions, cost and revenue streams, as well as financial calculations. The deployment of the framework has been described by theoretical examples. As a next step, the application of the model on the baseline and sustainable airport scenario has to be carried out. This will provide results through the estimation of the impact of scenario-specific investments, as well as process and infrastructure changes with respect to both analysed scenarios. The resulting scenario-specific financial statements, associated graphical analysis, and conclusions will provide evidence about the model's applicability.

Validating the model based on historic data is a critical next step. This will enhance the reliability and generalisability of the framework and can be used to refine the model's parameters, assumptions and outputs. In a subsequent step, sensitivity analyses can be conducted to demonstrate how the cash flow is affected by individual parameters such as investment volume or timing. This process helps to better understand the critical influencing factors and the associated risks. Further research is necessary to refine the methodology, particularly concerning the identification of investments with the most significant impact on the sustainable transformation of airports. Advanced techniques such as real option analysis or Monte Carlo simulations could be employed to enhance the precision of investment evaluations. Identifying the key drivers that maximise airport sustainability while maintaining economic feasibility is an area for future exploration.

References

Air Transport Research Society (2022): ATRS Airport Benchmarking Report. Global standards for airport excellence 2022. Available online at https://www.atrsworld.org/airport-benchmarking.

Airport Council International (2012): Airport Performance Benchmarking. Airport Performance Measures 2012. Available online at https://store.aci.aero/product/a-guide-to-airport-performance-measures/.

Di Vaio, Assunta; Varriale, Luisa (2020): SDGs and airport sustainable performance: Evidence from Italy on organisational, accounting and reporting practices through financial and non-financial disclosure. In Journal of Cleaner Production (249), Article 119431, pp. 2–3. Available online at https://doi.org/10.1016/j.jclepro.2019.119431.

Gronau, Steven; Hoelzen, Julian; Mueller, Tobias; Hanke-Rauschenbach, Richard (2023): Hydrogen-powered aviation in Germany: A macroeconomic perspective and methodological approach of fuel supply chain integration into an economy-wide dataset. In International Journal of Hydrogen Energy 48 (48), Article 5348. DOI: 10.1016/j.ijhydene.2022.10.168.

Hamburg Airport (2025): Windpark Heidmoor. Ein Projekt von Hamburg Airport. Edited by Hamburg Airport. Hamburg Airport. Available online at https://wind-heidmoor.de/, checked on 4/23/2025.

Koch, Benjamin (2006): Entwicklungsplanung für Flughafengesellschaften. Entscheidungsunterstützung durch die integrierte Marktprognose- und Finanzmodellierung. DOI: 10.1007/978-3-658-24336-4.

Monsalud, Andrew; Ho, Denny; Rakas, Jasenka (2015): Greenhouse gas emissions mitigation strategies within the airport sustainability evaluation process. In Sustainable Cities and Society 14, pp. 414–424. DOI: 10.1016/j.scs.2014.08.003.

Weiss, Marco (2020): Ein Konzept zur Sozio-Ökoeffizienz-Analyse des Lufttransportsystems mit Anwendung an der Systemkomponente Flughafen. Dissertation. Available online at https://elib.dlr.de/134776/.