The influence of sustainability measures on the connectivity of a hub and spoke airline network

A computational analysis

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by

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Ymie Neuteboom
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List of Abbreviations

ASK	Available Seat Kilometre
CNU	Connectivity Units
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DOC	Direct Operating Costs
ETS	Emissions Trading System
EU	European Union
FLY	Flying time
FREQ	Frequency
GWP	Global Warming Potential
H&S	Hub-and-Spoke
ICAO	International Civil Aviation Organisation
IOC	Indirect Operating Costs
LLC	Low Cost Carrier
MAXT	Maximum Perceived Travel Time
MILP	Mixed Integer Linear Programming
NST	Non-Stop Travel Time
OD	Origin-Destination
OLS	Ordinary Least Squares
PM	Particle Matter
PSO	Public Service Obligation
PTT	Perceived Travel Time
QUAL	Quality of Connections
RF	Radiative Forcing
RFI	Radiative Forcing Index
SAF	Sustainable Aviation Fuel
TRF	Transfer time

Introduction

This project originated from a growing awareness of the aviation industry's environmental impact, particularly concerning CO_2 emissions. As global interest in sustainable practices increases, the need for innovative solutions in aviation has never been more pressing. This project seeks to address the challenges faced by airlines and airports in maintaining operational efficiency while reducing their environmental footprint.

The primary goal of this project is to explore and develop strategies that allow KLM and Schiphol Airport to operate sustainably without compromising their vital hub functions. By focusing on emission reduction while maintaining connectivity, the project aims to contribute to the ongoing dialogue surrounding aviation sustainability and provide actionable solutions for industry stakeholders.

This project was partially developed with flight data from KLM Royal Dutch Airlines, which provided insights into operational practices and constraints. Engaging with KLM allowed for a better understanding of the complexities involved in airline planning and the importance of maintaining a balance between growth and sustainability. Their expertise guided the development of a practical framework that could be implemented within existing airline operations.

What sets this project apart is its integrative approach, combining theoretical research with practical applications in a real-world context. From a societal perspective, this project contributes to the broader efforts of reducing greenhouse gas emissions and improving air quality for communities surrounding airports. By developing frameworks that allow airlines to operate sustainably, the project addresses urgent environmental concerns while supporting economic growth in the aviation industry.

This thesis report is organised as follows : In Part I, the scientific paper is presented. Part II contains the relevant Literature Study that supports the research. Finally, in Part III, supporting work is presented in the form of the validation process and additional model analysis.

I

Scientific Paper

The influence of sustainability measures on the connectivity of a hub and spoke airline network

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This study investigates the impact of CO_2 emission limitations on the connectivity and profitability of a hub-and-spoke airline network, with a specific focus on Schiphol Airport and KLM Royal Dutch Airlines. As sustainability becomes increasingly critical, the aviation industry faces mounting pressure to reduce its environmental footprint without compromising operational efficiency. This research employs a Mixed Integer Linear Programming (MILP) model to simulate airline operations under CO_2 constraints. Using synthetic flight data and OpenAP for accurate emissions estimation, the model optimises fleet composition, flight scheduling, and passenger flow while balancing profitability and emissions reduction. The study explores the potential of fleet renewal to mitigate the negative effects of emission caps on both connectivity and revenue. The findings demonstrate that significant emission reductions can be achieved through strategic fleet planning, with minimal impact on the airline's network and financial performance. This research provides a viable framework for integrating environmental considerations into long-term airline planning, contributing to the ongoing efforts to reduce aviation's environmental impact while maintaining its economic and operational benefits.

Index Terms—Airline operations, Amsterdam Schiphol Airport, MILP, connectivity, hub and spoke airline, sustainability, airline economics, airline emissions, KLM Royal Dutch Airlines

1 Introduction

As the interest in tackling the global warming and air quality problems has been growing worldwide, the aviation industry can not fall behind. The aviation industry was responsible for 2.5% of the global emission of CO_2 in 2018 and is expected to keep growing [1]. CO_2 is not the only problem. Contrails, nitrogen oxides and particulate matter are amongst the combustion products of aircraft engines that pose a threat to the environment and public health [2] [3] [4]. The airline fleet and network planning is a long-term strategic problem that is usually driven by market and financial factors [5]. However, sustainable goals are gaining increasing importance in these decisions. In line with this, new technologies and environmental policies have been proposed, but so far there is still a lot to win in aviation regarding sustainability.

Inhabitants of residential areas surrounding airports are protesting against the growth of airports due to noise and emissions. Schiphol airport in The Netherlands, the hub of KLM Royal Dutch Airlines, is situated in a densely populated area. In 2008 the capacity ceiling of the airport was set at 500,000 flight movements per annum [6]. Since 2017 Schiphol has been operating very close to this maximum capacity, while resistance of the population of Amsterdam and surrounding areas increased [7]. In the summer of 2022 the Dutch government proposed that Schiphol airport has to reduce the annual number of flights by 12% to 440,000 by November 2023 [8]. However, the government proposed to allow growth from 2027 onward under the condition that the nuisance will not exceed what 440,000 annual flights cause today [9].

The shrinkage of Schiphol airport will have big consequences for KLM. The airline uses Schiphol as a hub for its operations and operates around 70% of the flight movements [10]. Airport hubbing is a practice where an airline uses a particular airport as a central connecting point for its flights. The airline schedules its flights in such a way that passengers can conveniently transfer from one flight to another at the hub airport, often resulting in shorter travel times, increased frequency of flights, and a wider range of destination options. The hub function for KLM is one of the reasons that Schiphol is ranked number one in the ACI EUROPE Airport Industry Connectivity Report of 2022 [11]. A high airport connectivity has great benefits for the areas surrounding the airport and is one of the key drivers of economic growth [12] [13] [14].

From KLMs perspective connectivity is a critical component of their success as well. By offering a wide range of destinations, airlines can increase their revenue by attracting more passengers who prefer to fly to their desired destination on the same airline without having to self-connect. Airlines that are able to offer unique connections and itineraries tend to outperform their less connected rivals [15]. Airlines with a strong network have a competitive advantage over their rivals, as passengers are more likely to choose an airline that offers them a more convenient and efficient route to their destination, leading to customer loyalty, repeat business and positive recommendations [16]. It is therefore necessary to research other options to decrease emissions without having to weaken the hub function of KLM and connectivity of Schiphol Airport. This is especially important since de-hubbing of an airport is very likely to be irreversible [17]. In this work the possibilities and opportunities of using an airline planning framework to decrease aircraft emissions are researched. The goal is to find an approach that can contribute to a future where Schiphol connects The Netherlands to the rest of the world while operating within the limits of CO_2 emission.

2 Background

This chapter provides an overview of the essential concepts and policies that influence airline operations, with a focus on hub-and-spoke network carriers, sustainability efforts, and measures of connectivity. KLM, as a key player in the aviation industry, operates within a complex framework of policies and strategies aimed at optimising efficiency, reducing environmental impact, and maintaining connectivity. The following sections delve into these aspects, setting the stage for the analyses and discussions in subsequent chapters. In section 2.1 the KLM network is described, followed by section 2.2 about the various relevant sustainability policies. Finally different measures of connectivity are pointed out in section 2.3.

2.1 Hub-and-spoke airline planning

KLM is a H&S network carrier and operates with Schiphol Amsterdam Airport as its hub. A H&S network operates OD-pairs with flights connecting at the hub. This allows passengers with different origins and destinations to board the same flight and makes routes with lower demand profitable. To facilitate fast transfers, most hub airports work with connecting banks or waves. Passengers and cargo from the origins arrive at the hub at the start of the wave, have time to transfer to the connecting flight, and depart to their destinations at the end of the wave.

Even though this ensures quick transfers, there are downsides to this approach. During the waves, the hub operates at peak capacity, leading to congestion and increased emissions, while only limited capacity is utilised outside of the waves. To distribute resource usage more evenly, some airlines have introduced the concept of a rolling hub. In this system, arrivals and departures are spread throughout the day, reducing peak congestion but potentially resulting in longer transfer times for passengers.

2.2 Sustainability policies

Aviation is under increasing pressure to reduce its environmental impact, prompting the development of various sustainability policies at both the European and national levels. These policies aim to balance the growth of the aviation industry with the urgent need to address climate change. In this section, we explore some of the key policies shaping the sustainability landscape in aviation.

European Green Deal

The European Green Deal is a comprehensive plan to make the European Union's economy sustainable and achieve climate neutrality by 2050. It includes a wide range of policies and initiatives to reduce greenhouse gas emissions, increase the use of renewable energy, and promote sustainable agriculture and forestry. The European Green Deal also aims to create a circular economy and protect biodiversity. One of the key initiatives under the European Green Deal is Fit for 55. This is a package of legislative proposals that aims to reduce the EU's greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels [18] [19].

CORSIA

The International Civil Aviation Organisation (ICAO) adopted the emissions mitigation framework known as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA supports ICAO's goal of achieving carbon-neutral growth from 2020 onward. The pilot phase of CORSIA began in 2021, and by 2027, CORSIA aims to make participation mandatory for all ICAO member states [20]. While CORSIA sets out an ambitious plan, critics point out that ICAO's documents offer limited detail on how these goals will be achieved, suggesting a need for further clarity and actionable measures.

Dutch civil aviation policy memorandum

The Dutch civil aviation policy memorandum outlines goals to limit CO_2 emissions of Dutch aviation to 2005 levels by 2030, reduce them by 50% relative to 2005 by 2050, and reach zero emissions by 2070. To reinforce these targets, the Dutch government has proposed a CO_2 emission ceiling for the international aviation sector. This provides a clear framework for the sector to grow in a sustainable manner [21].

The research institute CE Delft conducted an assessment following the announcement of the CO_2 ceiling, investigating the implications of the measure. Multiple scenarios were considered, taking into account measures from the European Fit for 55 proposals, national climate policy, and socioeconomic development. Additionally, the assessment incorporated the government's recent announcement regarding capacity reduction at Schiphol. CE Delft identified three main policy framework options: CO_2 ceilings for airports, for fuel suppliers, or for airlines. The study concluded that without government intervention, Dutch aviation CO_2 emissions would likely exceed the targets in most scenarios [22] [23]. Notably, the study did not address the impact on Schiphol's connectivity or the airlines operating from the airport.

2.3 Measures of connectivity

Connectivity is generally defined as the degree to which nodes in a network are connected to each other [24]. In airline literature, many different approaches exist to defining the connectivity of airlines and airports. There are various indices and ratios used to measure and quantify connectivity at airports and within networks, taking into account factors such as the number of connections, flight times, and the attractiveness of connections. The Netscan connectivity model is widely acknowledged as a robust measure of connectivity, as it captures seat capacity while considering both direct and indirect connections. In this model, the quality of a connection contributes to the score as well, by accounting for transfer times [11]. Other notable connectivity measures include:

- **York Aviation Business Connectivity Index:** Captures the economic importance of destinations and measures the value of connectivity to businesses.
- **World Bank Air Connectivity Index:** Weights the value of a route based on the number of onward connections available, reflecting the benefits of hub airports.
- **IATA Connectivity Index:** Captures the importance of destinations based on the size of the final destination airport [25].

One significant advantage of the Netscan model is that the equations and methodologies used to calculate connectivity are well-documented in the literature, allowing researchers and industry professionals to apply or adapt them to their specific needs. The underlying calculations of the other connectivity models are not publicised by the developers. This makes it difficult for researchers and practitioners to reproduce the findings or understand the precise mechanisms that led to the results.

The Netscan model, by making its calculations available, not only ensures clarity but also enhances its credibility as a tool for analysing and comparing connectivity. This level of detail enables users to understand the specific factors that influence connectivity, such as seat capacity, direct and indirect connections, and transfer times, and how these factors are quantitatively integrated into the final score. In section 3.5 the full model is described.

3 Methodology

This research aims to evaluate the effect of CO_2 emission limitations on the Netscan connectivity score and profit of a a hub-and-spoke airline and the space to mitigate the potential loss in connectivity and profitability by renewing the fleet with more fuel efficient aircraft. The goal is to generate a daily schedule from which Netscan connectivity of the network can be calculated. In this section the method is described, starting with the simplifications in section 3.1. The next chapter is the description of the chosen solving method in section 3.2, followed by the description of the emissions model OpenAP that will be used to determine the CO_2 generated by the network in section 3.3. After that section 3.4 describes the inputs of the model, including fleet composition, demand, ticket fares, operating costs and airports in the network. Section 3.5 gives a full description of the MILP model including mathematical formulations of the objective function and constraints, as well as the Netscan connectivity model mentioned in section 2.3 of the previous chapter. Finally in section 3.6 the computational set-up used for this research is evaluated.

3.1 Model simplifications

To address the problem of optimising fleet composition and network performance under environmental and operational constraints, the model includes several simplifications. These simplifications allow for more efficient computation and focus on the key decision variables without losing the relevance of the results. Below, the main assumptions are discussed and it is explained why they are not expected to affect the validity of the study's conclusions.

Flights start at Schiphol

In the model, aircraft are allowed to start their flights in Amsterdam but are not required to return to the hub by the end of the day. This flexibility mirrors the real-world operations of airlines, where aircraft may end their day at different airports rather than returning to the primary hub. This assumption allows the model to more accurately reflect network optimisation decisions and provides operational flexibility in response to environmental and operational constraints.

By not forcing aircraft to return to Amsterdam, the model can capture the potential benefits of more efficient scheduling, where flights to distant or less-connected destinations do not need to be constrained by the need for the aircraft to return to the hub. This enables better utilisation of the fleet, as aircraft can serve intercontinental routes.

Moreover, this flexibility is particularly relevant in hub-and-spoke operations, where long-haul flights or connecting routes may naturally end at spokes rather than the hub. Allowing aircraft to stay overnight at different airports aligns with real-world practices, where overnight stays at spokes can enhance network connectivity, reduce operational costs, and balance maintenance or crew schedules. Thus, this approach enriches the model by adding realistic scheduling flexibility, which is crucial for evaluating fleet performance, connectivity, and profitability under environmental constraints.

Distance is modelled as arc length

Another simplification is that distances between airports are calculated as arc lengths, assuming a spherical Earth. While this ignores some real-world complexities such as air traffic control routing, weather diversions, and geopolitical restrictions, the arc length approximation is a standard and accepted method in network optimisation. It provides a close enough estimate of actual flight distances for the purpose of fuel consumption and emissions calculations. Moreover, in the context of an optimisation model that compares different fleet compositions and operational scenarios, the relative differences in flight distances are more important than absolute accuracy. As all scenarios use the same distance metric, the conclusions drawn from the comparisons remain valid.

Fixed number of seats per aircraft

The model assumes that each aircraft type has a fixed number of seats, rather than considering different seating configurations based on route length or demand variability. This simplification allows for a more straightforward comparison of fleet efficiency without introducing the complexity of dynamic capacity management. In practice, while airlines may adjust seating configurations to suit different routes or market conditions, these adjustments tend to be marginal compared to the broader decisions related to fleet renewal and CO_2 emissions. By focusing on a fixed number of seats, the model captures the essential relationship between aircraft size, fuel consumption, and profitability, while avoiding unnecessary complications that would have minimal impact on the overall findings.

No competition

Finally, the model does not account for competition from other airlines, focusing solely on the network optimisation of a single airline. While competition is a significant factor in real-world airline operations, its absence in this model is justified because the study's primary objective is to examine how different fleet compositions perform under environmental regulations and operational constraints. By isolating the airline from competitive pressures, the model allows us to focus on the intrinsic relationships between fleet renewal, CO_2 caps, profitability, and connectivity. Including competition would introduce additional variables and noise that may obscure the impact of the key decision variables being studied. Moreover, many of the insights gained from this isolated analysis can be extended to competitive environments, as the core trade-offs between fleet efficiency, emissions, and connectivity remain applicable.

3.2 Mixed integer linear programming

The chosen solution method is mixed integer Linear Programming (MILP) since it has the capacity to handle the complexity and specificity of real-world decision-making problems. MILP allows for the integration of both continuous and discrete variables, enabling the precise modelling of scenarios where decisions involve binary or integer choices, such as the selection of fleet compositions or scheduling options. This flexibility is essential when dealing with constraints and objectives that require a combination of different types of decisions, as it allows for the simultaneous optimisation of diverse factors within a unified framework. Krömer et al. describes a MILP approach for a sustainable airline planning and scheduling model which demonstrates that airlines can reduce there number of flights and therefore their emissions without significant profit loss [26]. Lohatepanont and Barnhart state that even though MILP is traditionally used for frequency planning, it can also be used effectively for timetable development [27].

3.3 Emissions calculation

To accurately estimate CO_2 emissions for each flight, this study uses OpenAP, an open-source aircraft performance software. OpenAP estimates fuel consumption and emissions based on real flight trajectory data, incorporating factors such as aircraft type, flight duration, and operational conditions [28].

By leveraging OpenAP, the research can obtain precise emissions data for each flight segment. This detailed information is crucial for assessing how different fleet compositions and operational strategies affect overall CO_2 output. Integrating these estimates into the optimisation model helps evaluate the impact of CO_2 emission limits on connectivity and profitability.

OpenAP's open-source nature also ensures transparency, allowing for validation and adjustment of emissions calculations as needed. This strengthens

TABLE 1
Aircraft in fleet for baseline schedule

Aircraft	Seats [-]	Range [km]
A330-300	440	8200
A321	220	6000
A320	180	5000

TABLE 2
Replacement aircraft for fleet renewal

Replacement	Seats [-]	Range [km]
A330-200	406	8200
B737-900	215	4300
e190	114	3300

the credibility of the study and supports effective strategies for reducing emissions in the airline industry.

3.4 Model inputs

This section outlines the key inputs used for modelling fleet renewal effects within a CO_2 restrictions framework. The data includes details on aircraft, demand, ticket fares, operating costs, and a representative sample of airports within the KLM network, providing a foundation for analysing fleet operations and network impact.

Aircraft

As on of the aims of this study is to find the effects of fleet renewal on the network within a CO_2 restrictions framework, a list of aircraft and their replacement is compiled based on availability in OpenAP and comparability to the current KLM fleet. In the synthetic flight data that is provided the fleet consists of three aircraft types and since this data is used throughout the project, this was chosen to do as well. In table 1 and table 2 the relevant aircraft data of both the baseline fleet and the replacement aircraft are shown. For aircraft in the current KLM fleet, the number of seats correspond to their current seat layout [29]. Aircraft not currently operated by the airline are equipped with the average number of seats as used in OpenAP [28].

Demand, ticket fares and operating costs

The demand for each origin-destination (OD) pair is extracted from the available synthetic flight data, which includes a detailed weekly flight schedule along with passenger information for both direct and transfer flights. This dataset provides the number of passengers travelling from each origin to each destination, irrespective of whether they are direct or transfer passengers. To simplify the demand estimation process, the weekly passenger totals are averaged to obtain a daily demand figure. This approach avoids the complexities of demand forecasting, revenue management, and competitive impact analysis, focusing solely on a straightforward demand calculation.

For ticket fares, the dataset provides average fare information for each OD pair. This average fare is used directly in the analysis, aligning with the approach taken for demand estimation. This simplifies fare considerations without delving into dynamic pricing or competition effects.

Operating costs are derived from a dataset that includes both direct operating costs (DOC) and indirect operating costs (IOC) per aircraft type for the currently operated city pairs. To estimate the total costs for each flight, an Ordinary Least Squares (OLS) regression model is employed. This model estimates the relationship between the cost (dependent variable, Y) and distance (independent variable, X) using the following linear equation:

$$y = Bx + e \tag{1}$$

Here, B represents the coefficient that quantifies the relationship between distance and cost, x is the distance, and e is the error term.

To estimate the coefficient B, the OLS regression is performed using known combinations of distances and costs. The coefficient B is calculated using the formula:

$$B = \left(X^T X\right)^{-1} X^T Y \tag{2}$$

This calculation is executed in Excel, providing an estimate for B based on the available data. With B determined, the regression model is used to predict costs for connections where direct cost data is not available.

The OLS regression is appropriate for this context due to the linear relationship expected between distance and operating costs. Assumptions underlying this model include linearity and homoscedasticity, which means the variance of the errors should be constant across all levels of the independent variable. This method ensures that cost estimations for various OD pairs are based on a robust statistical foundation.

Airports

The complete data set encompasses 135 airports within the KLM network. These can be found in table 3 to table 5. Nearby airports play a crucial role in feeding traffic to long-haul flights. By strategically scheduling shorter flights from these regional airports to the hub, airlines can bring together passenger demand from various locations, thereby maximising the number of travellers boarding long-distance flights. This feeder service helps ensure that long-haul flights depart with higher passenger loads, which is vital for maintaining profitability and plays a role in the connectivity score of the network as well.

3.5 Model set-up

The core of this research revolves around an airline planning tool, which is formulated as a linear programming (LP) model. This model simulates airline

TABLE 3
Short-distance airports from AMS (under 1,500 km)

Airport code	City	Distance [km]	Airport code	City	Distance [km]
ABZ	Aberdeen	705	FLR	Florence	1,060
AES	Ålesund	990	FRA	Frankfurt	360
AMS	Amsterdam	0	GDN	Gdańsk	925
ARN	Stockholm	1,140	GOA	Genoa	1,025
BGO	Bergen	890	GRZ	Graz	995
BHD	Belfast	745	GVA	Geneva	685
BHX	Birmingham	440	HAJ	Hanover	330
BIO	Bilbao	1,070	HAM	Hamburg	365
BLL	Billund	475	HUY	Humberside	470
BLQ	Bologna	1,045	IBZ	Ibiza	1,550
BOD	Bordeaux	920	INV	Inverness	905
BRE	Bremen	300	KRS	Kristiansand	870
BRS	Bristol	500	LBA	Leeds	465
BRU	Brussels	160	LCY	London City	335
BSL	Basel	685	LHR	London Heathrow	375
CDG	Paris	400	LIN	Milan Linate	830
CPH	Copenhagen	625	LPI	Linköping	1,035
CWL	Cardiff	550	LUX	Luxembourg	320
DRS	Dresden	680	LYS	Lyon	730
DUS	Düsseldorf	180	MME	Durham	500
EDI	Edinburgh	665	MPL	Montpellier	950
SOU	Southampton	480	ZRH	Zurich	610

TABLE 4
Medium-distance airports from AMS (1,500 – 3,500 km)

Airport code	City	Distance [km]	Airport code	City	Distance [km]
AAL	Aalborg	700	IST	Istanbul	2,210
AGP	Málaga	1,887	KBP	Kyiv	1,800
ATH	Athens	2,170	KRK	Krakow	1,060
BCN	Barcelona	1,240	LED	St. Petersburg	1,770
BUD	Budapest	1,150	LIS	Lisbon	1,865
CAG	Cagliari	1,475	MAD	Madrid	1,450
CTA	Catania	1,885	MAN	Manchester	520
DUB	Dublin	750	MXP	Milan	825
FCO	Rome	1,290	NCE	Nice	980
GLA	Glasgow	710	OTP	Bucharest	1,850
GOT	Gothenburg	765	PRG	Prague	1,030
HEL	Helsinki	1,830	TLV	Tel Aviv	3,300
TRD	Trondheim	1,650	VCE	Venice	940
VIE	Vienna	970	WAW	Warsaw	1,180
ZAG	Zagreb	1,180			

operations by optimising for profitability under various constraints, including demand, fleet capacity, and operating costs.

Sets, decision Variables, and parameters

The model considers three primary sets, which define the scope of the problem:

N : Set of airports in the network
K : Set of aircraft types available for scheduling
T : Set of time slots across the planning horizon

The decision variables in the model determine the flow of passengers and the allocation of aircraft:

$x_{ijt_ot_a}$ Direct passenger flow from airport i to airport j, originating in time slot t_o and departing in time slot t_a

$w_{ijt_ot_at_2}$ Indirect passenger flow from airport i to airport j, originating in time slot t_o, departing in time slot t_a, and transferring at the hub in time slot t_2

z_{ijkt_a} Number of flights from airport i to airport j using aircraft type k departing in time slot t_a

y_{ikt} Number of aircraft of type k available at airport i in time slot t

The model uses several key parameters that define the operational characteristics:

TABLE 5
Long-Distance Airports from AMS (over 3,500 km)

Airport code	City	Distance [km]	Airport code	City	Distance [km]
ATL	Atlanta	6,960	JFK	New York	5,870
BOG	Bogotá	8,875	KIX	Osaka	9,365
BOM	Mumbai	6,755	KUL	Kuala Lumpur	10,180
CGK	Jakarta	11,205	LAX	Los Angeles	8,987
CTG	Cartagena	8,560	LIM	Lima	10,230
CTU	Chengdu	7,900	MEX	Mexico City	9,240
DEL	Delhi	6,370	MIA	Miami	7,460
EZE	Buenos Aires	11,360	MNL	Manila	10,475
FOR	Fortaleza	7,280	MSP	Minneapolis	6,760
GIG	Rio de Janeiro	9,320	ORD	Chicago	6,635
GRU	São Paulo	9,650	PEK	Beijing	7,860
GYE	Guayaquil	9,650	PVG	Shanghai	8,925
HGH	Hangzhou	8,800	SCL	Santiago	11,950
HKG	Hong Kong	9,160	SFO	San Francisco	8,905
IAD	Washington D.C.	6,220	SLC	Salt Lake City	8,115
IAH	Houston	8,200	TPE	Taipei	9,775
IKA	Tehran	4,190	UIO	Quito	9,440
YEG	Edmonton	7,040	YUL	Montreal	5,475
YVR	Vancouver	7,670	YYC	Calgary	7,310
YYZ	Toronto	6,010			

BT_{ij} Block time from airport i to airport j, including turnaround times
d_{ij} Distance between airport i and airport j
F_k Number of aircraft in the fleet for aircraft type k
f_{ij} Ticket fare from airport i to airport j
H Hub index used to indicate the airline's hub airport
OC_{ij} Operating cost for a flight from airport i to airport j
q_{ijt} Demand for travel from airport i to airport j in time slot t
S_k Seat capacity of aircraft type k

Objective function

The objective of the model is to maximise the airline's profit, calculated as the difference between total revenue from ticket sales and the operating costs. This is formulated as:

$$\text{Maximise Profit} = \sum_{i\in N}\sum_{j\in N}\sum_{t_o\in T}\sum_{t_a\in T}\sum_{t_2\in T}\left[f_{ij}\times(x_{ijt_ot_a}+w_{ijt_ot_at_2}) - \sum_{k\in K} OC_{ij}\times z_{ijkt_a}\right] \quad (3)$$

The profit maximisation involves two primary components:

- **Revenue:** Derived from direct and indirect passenger flows, each multiplied by the corresponding ticket fares.
- **Costs:** Represented by the operating costs associated with each flight, calculated per aircraft type.

By optimising the decision variables, the model aims to allocate flights and passenger flows in a way that maximises profitability while adhering to operational constraints such as fleet availability, seat capacity, and demand fulfilment.

Pre-processing of decision variables

The decision variables that should be zero are filtered out for efficient optimisation. This ensures that unnecessary entries are excluded, maintaining a focus on realistic scenarios where aircraft are located. This formulation ensures that only the realistic flows of passengers are considered, avoiding unnecessary computational complexity by excluding infeasible or irrelevant scenarios. In the airline scheduling optimisation model, the decision variable $x_{ijt_ot_a}$ represents the number of passengers flying from airport i to airport j with a departure time slot t_o and arrival time slot t_a. Handling this variable in an efficient manner is critical due to the large number of possible combinations of i, j, t_o, and t_a, many of which are not feasible or relevant in practice. Passenger flow x is zero if the departure airport is de destination airport and if both departure and destination airport are not the hub. Passengers are assumed to be willing to depart two hours earlier or two hours later than their desired departure time, so when the actual departure time of is longer than two hours before or after their original demand departure time the values of $x_{ijt_ot_a}$ are excluded. This can be seen in equation 4 to equation 6

$$x_{ijt_ot_a} = 0, \quad \forall(i,j) \text{ where } i = j \quad (4)$$

$$x_{ijt_ot_a} = 0, \quad \forall(i,j) \text{ where } i \neq \text{hub} \ \& \ j \neq \text{hub} \quad (5)$$

$$x_{ijt_ot_a} = 0, \quad \forall(t_o,t_a) \text{ where } t_o - t_a > 2 \quad (6)$$

In the airline scheduling optimisation model, the decision variable y_{ikt} represents the number of aircraft of type k located at airport i during time slot t. This variable ensures the availability of aircraft when planning a flight. The presence of aircraft at airports is constrained by several operational factors. At the beginning of the day ($t = 0$), only aircraft stationed at the hub (i = hub_index) should have non-zero values. All other airports should have zero aircraft. This can be seen in equation 7.

$$y_{ikt} = 0 \quad \forall(i, t) \text{ where } t = 0 \text{ \& } i \neq \text{ hub} \tag{7}$$

In the airline scheduling optimisation model, the decision variable z_{ijkt_a} represents the number of aircraft of type k that depart from airport i to airport j at departure time slot t. To efficiently manage this variable, infeasible or irrelevant scenarios are excluded. The decision variable z_{ijkt_a} is excluded from the optimisation when the airport of origin i and the destination airport j are both a spoke of the hub-and-spoke network, as well as when the flight time would exceed the length of the day. This can be seen in equation 8 to equation 10. If the distance from airport i to airport j exceeds range of aircraft type k, the entry of z_{ijkt_a} is excluded as well.

$$z_{ijkt_a} = 0 \quad \forall(i, j) \text{ where } i \neq hub \text{ \& } j \neq \text{ hub} \tag{8}$$

$$z_{ijkt_a} = 0 \quad \forall(i, j) \text{ where } i = j \tag{9}$$

$$z_{ijkt_a} = 0 \quad \forall(i, j) \text{ where } t_a + BT \leq t_{max} \tag{10}$$

$$z_{ijkt_a} = 0 \quad \forall(i, j) \text{ where } d_{ij} \leq R_k \tag{11}$$

Decision variable $w_{ijt_ot_at_2}$ represents the number of transfer passengers with original demand time t_o and actual departure time t_a flying from airport i to airport j with a transfer at the hub at t_2. This decision variable has a very high number of possible combinations, which makes it more critical to reduce the size. As can be seen in equation 12 to equation 15 flow of transfer passengers is impossible when when the actual departure time is longer than two hours before or after their original demand departure time. Also $w_{ijt_ot_at_2}$ should be set to zero when either i or j is the hub, and when the transfer time is not sufficient to catch the second leg of the flight.

$$w_{ijt_ot_at_2} = 0 \quad \forall(i, j) \text{ where } i = j \tag{12}$$

$$w_{ijt_ot_at_2} = 0 \quad \forall(t_o, t_a) \text{ where } |t_o - t_a| > 2 \tag{13}$$

$$w_{ijt_ot_at_2} = 0 \quad \forall(i, j, t_2) \text{ where } t_2 < t_a + BT_{ij} + TF_{min} \tag{14}$$

$$w_{ijt_ot_at_2} = 0 \quad \forall(i, j, t_2) \text{ where } i = hub \text{ or } j = hub \tag{15}$$

Constraints

The constraints that describe the boundaries in which the optimisation should fit that do not describe a necessity to be zero are used in the LP model are described below. Constraint 16 makes sure the total number of passengers transported from airport i to airport j does not exceed the demand.

$$x_{ijt_ot_a} + w_{ijt_ot_at_2} \leq q_{ijt_o}, \qquad \forall i, j \in N \tag{16}$$

The capacity constraint ensures that there are no more passengers transferred than there are seats available on the flights that serve these routes. The number of passengers on a flight consists of direct flow passengers, transfer passengers on the first leg of their journey and passengers on their second leg, as shown in constraint 17 to 19.

$$\sum_{t_o \in T} x_{ijt_ot_a} + \sum_{m \in N, m \neq i} \sum_{t_1 \in T} \sum_{t_o \in T} w_{mjt_1t_ot_a} \leq \sum_{k \in K} z_{ijkt_a} S_k \cdot LF_{max}, \quad \forall j \in N,\, t_a \in T \quad \text{if } i = \text{hub} \tag{17}$$

$$\sum_{t_o \in T} x_{ijt_ot_a} + \sum_{m \in N, m \neq j} \sum_{t_2 \in T} \sum_{t_o \in T} w_{imt_ot_at_2} \leq \sum_{k \in K} z_{ijkt_a} S_k \cdot LF_{max}, \quad \forall i \in N,\, t_a \in T \quad \text{if } j = \text{hub} \tag{18}$$

$$\sum_{t_o \in T} x_{ijt_ot_a} \leq \sum_{k \in K} z_{ij}^{kt_a} S_k \cdot LF_max, \quad \forall i, j \in N,\, t_a \in T \quad \text{if } i \neq \text{hub and } j \neq \text{hub} \tag{19}$$

Decision variable y_{ikt} is used as a helper to keep track of available aircraft in the network. In the morning all aircraft should be at the hub as seen in constraint 20. Constraint 21 is used similarly to have all aircraft return to the hub in the evening.

$$y_{ikt} = F_k, \quad \forall k \in K \quad \text{if } t = 0 \text{ and } i = \text{hub} \tag{20}$$

$$y_{ikt} = F_k, \quad \forall k \in K \quad \text{if } t = t_{max} \text{ and } i = \text{hub} \tag{21}$$

Constraint 22 links helper decision variable y_{ikt} to the rest of the model by ensuring there is an aircraft of type k available to facilitate flight z_{ijkt}.

$$y_{ikt} \geq \sum_{j \in N} z_{ijkt}, \quad \forall t \in T, \forall i \in N, \forall k \in K, \text{ if } i \neq \text{hub} \tag{22}$$

Constraint 23 makes sure that there are no more aircraft stationed at airport i than there are available in the fleet.

$$y_{ikt} \leq F_k, \quad \forall i \in N, \quad \forall k \in K, \quad \forall t \in T \tag{23}$$

Constraint 24 balances the number of aircraft for each time period to the sum of incoming and outgoing aircraft according to decision variable z_{ijkt}.

$$y_{ikt} = y_{ik(t-1)} + \sum_{j \in N} z_{jik(t-BT_{ji})} - \sum_{j \in N} z_{ijkt}, \quad \forall i \in N, \quad \forall k \in K, \quad \forall t \in T, \quad t \neq 0, \quad t \geq BT_{ji} \tag{24}$$

The optimisation model aims to solve the airline's network scheduling problem by maximising the operational profit under various constraints such as aircraft availability, demand, and operational costs. This optimisation process is carried out independently of the connectivity assessment and focuses on generating an optimal flight schedule based on the given inputs.

After the optimisation has been performed and the resulting schedule is generated, the quality of the network is evaluated using the Netscan connectivity model. The connectivity model, which is applied as a post-processing step, calculates the overall network connectivity by computing connectivity units (CNU) for each connection. This connectivity score serves as a key performance indicator (KPI) to assess how well the optimised network facilitates passenger flows, beyond just financial metrics.

Thus, the optimisation and connectivity evaluation are distinct processes. The optimisation determines the flight schedule, while the connectivity model provides an after-the-fact assessment of the network's effectiveness in terms of passenger connectivity. The connectivity assessment is described in the following chapter.

Netscan connectivity model

The Netscan connectivity model rates every connection in the network by calculating so called connectivity units (CNU) using equation 25 to equation 28. The sum of CNU for every connection in the network, is the total NETSCAN connectivity score, which can be compared for different scenarios.

The calculation process is outlined as follows:

1) **Maximum perceived travel time (MAXT):**

$$MAXT = (3 - 0.075 \times NST) \times NST \quad (25)$$

where NST is the *Non-Stop Travel Time*. This formula sets a cap on acceptable travel time, which decreases as more sectors are added.

2) **Perceived Travel Time (PTT):**

$$PTT = FLY + (3 \times TRF) \quad (26)$$

This equation calculates the perceived travel time, considering both flight time FLY and transfer time TRF, with a heavier weight assigned to transfers.

3) **Quality of Connection (QUAL):**

$$QUAL = 1 - \frac{PTT - NST}{MAXT - NST} \quad (27)$$

The quality of a connection is determined by how close the perceived travel time PTT is to the ideal *Non-Stop Travel Time* NST, scaled by the maximum acceptable time $MAXT$.

4) **Connectivity Units (CNU):**

$$CNU = QUAL \times FREQ \quad (28)$$

The final CNU is calculated by multiplying the quality of the connection $QUAL$ by the frequency $FREQ$ of the connection.

The total Netscan connectivity score Total_CNU for the network is the sum of the connectivity units (CNU) across all connections:

5) **Connectivity of the network**

$$\text{Netscan Connectivity} = \sum_{i,j} CNU_{ij} \quad (29)$$

where CNU_{ij} represents the connectivity units for the connection from airport i to airport j. This sum provides the overall connectivity score for the network.

3.6 Computational set-up

The optimisation tasks for this research were executed on a personal computing system with the following specifications:

- **Processor:** 2.3 GHz Dual-Core Intel Core i5
- **Memory:** 8 GB 2133 MHz LPDDR3 RAM

This configuration is a standard setup for personal or office computing environments. It features a dual-core processor with a clock speed of 2.3 GHz, which is adequate for general computing tasks and moderate optimisation problems. The 8 GB of LPDDR3 RAM provides sufficient memory for handling a variety of applications, though it may be limiting for very large-scale optimisation problems or highly complex models.

4 Case Study

For the case studies, three key variables were modified: the CO_2 cap imposed on the airline's operations, capping the number of daily flight movements and the percentage of new, more environmentally-friendly aircraft in the fleet as described in section 3.4. These fleet composition scenarios are described in section 4.1. These variables were adjusted across 16 scenarios for CO_2 cap and 16 scenarios for flight movement cap, divided into four primary groups based on fleet composition. This is elaborated on in section 4.2 and section 4.3.

4.1 Fleet composition scenarios

1) **100% old aircraft:** In scenarios 1 to 4, the airline operates exclusively with the old aircraft fleet. The fleet composition includes aircraft with seat capacities of 440, 220, and 180, distributed across different fleet sizes.
2) **33% new aircraft:** In scenarios 5 to 8, 33% of the fleet is composed of newer, more fuel-efficient aircraft. The fleet now includes aircraft with varying seat capacities: 440, 406, 220, 215, 180, and 114, distributed across different fleet sizes.
3) **66% new aircraft:** In scenarios 9 to 12, 66% of the fleet consists of new aircraft. The same variety of seat capacities as in the previous scenarios is maintained, with the distribution

of fleet sizes adjusted to reflect the increased proportion of new aircraft.

4) **100% new aircraft:** In scenarios 13 to 16, the airline operates entirely with new aircraft. The fleet now consists of aircraft with seat capacities of 406, 215, and 114, distributed across different fleet sizes.

4.2 CO_2 cap & fleet renewal scenarios

Each fleet composition scenario is analysed under four different CO_2 emission caps:

1) **Scenario A: low CO_2 cap**
   - Maximum CO_2 allowance: 14 million kg
   - This scenario applies to fleet composition scenarios 1, 5, 9, and 13. It evaluates the effects of a low CO_2 cap on the airline's operations and fleet efficiency.
2) **Scenario B: moderate CO_2 cap**
   - Maximum CO_2 allowance: 13 million kg
   - This scenario features a moderate CO_2 cap, applied to fleet composition scenarios 2, 6, 10, and 14. It explores the impact of a more stringent emissions restriction on the overall performance of the fleet.
3) **Scenario C: stringent CO_2 cap**
   - Maximum CO_2 allowance: 12 million kg
   - This scenario introduces a stringent CO_2 cap, applied to fleet composition scenarios 3, 7, 11, and 15. It assesses the effects of tight emissions restrictions on operational efficiency and fleet utilisation.
4) **Scenario D: very stringent CO_2 Cap**
   - Maximum CO_2 allowance: 11 million kg
   - This scenario represents the most restrictive CO_2 cap, applied to fleet composition scenarios 4, 8, 12, and 16. It evaluates the impact of very tight emissions restrictions on fleet performance and overall airline profitability.

This combination of fleet composition and CO_2 caps results in a total of 16 unique scenarios, covering a wide range of operational and environmental conditions. In table 6 the numbering of the scenarios is covered.

TABLE 6
Scenarios with CO_2 caps and fleet renewal percentages

CO_2 cap [kg]	**15**	**13**	**11**	**9**
0% New Aircraft	1	2	3	4
33% New Aircraft	5	6	7	8
66% New Aircraft	9	10	11	12
100% New Aircraft	13	14	15	16

4.3 Restriction on the daily number of flights & fleet renewal scenarios

In addition to analysing the impact of CO_2 emission caps on airline network connectivity, another critical sustainability measure under investigation is the restriction on the daily number of flights. This restriction is examined in conjunction with fleet renewal strategies to assess its effects on the operational efficiency and environmental footprint of the airline network.

The restriction on the daily number of flights aims to limit the total number of flights an airline can operate each day. This measure is designed to reduce the overall environmental impact of the airline by decreasing the total number of aircraft movements. By enforcing a cap on daily flights, the airline can potentially lower its CO_2 emissions and fuel consumption, contributing to its sustainability goals.

The impact of this restriction is evaluated in several scenarios, varying by the extent of fleet renewal and the level of daily flight limitations. The primary objective is to determine how these restrictions affect network connectivity and operational efficiency. This analysis contributes to a comprehensive understanding of how flight restrictions and fleet renewal can be strategically combined to enhance the sustainability of airline operations while maintaining network performance and efficiency.

1) **Scenario A: low flight cap**
   - Maximum number of daily flights: 400 flights
   - This scenario represents a baseline with a low cap on the number of flights, applied to fleet composition scenarios 17, 21, 25, and 29. It examines the effects of restricting flight numbers while maintaining a static fleet composition.
2) **Scenario B: moderate flight cap**
   - Maximum number of daily flights: 375 flights
   - This scenario features a moderate cap on daily flights, applied to fleet composition scenarios 18, 22, 26, and 30. It explores the impact of a more stringent flight restriction in combination with partial fleet renewal.
3) **Scenario C: stringent flight cap**
   - Maximum number of daily flights: 350 flights
   - This scenario introduces a stringent cap on the number of flights, applied to fleet composition scenarios 19, 23, 27, and 31. It assesses the effects of tight flight restrictions alongside a higher level of fleet renewal.
4) **Scenario D: very stringent flight cap**
   - Maximum number of daily flights: 325 flights
   - This scenario represents the most restrictive flight cap, applied to fleet composition scenarios 20, 24, 28, and 32. It evaluates the impact of very tight flight restrictions in conjunction with full fleet renewal.

TABLE 7
Scenarios with caps on the daily number of flights and fleet renewal percentages

Daily flights [-]	400	375	350	325
0% New Aircraft	17	18	19	20
33% New Aircraft	21	22	23	24
66% New Aircraft	25	26	27	28
100% New Aircraft	29	30	31	32

5 Results

This section presents the outcomes of the simulations conducted to evaluate the impact of different sustainability measures and fleet compositions on airline operations. The analysis begins with a baseline scenario, in which no sustainability restrictions are imposed in section 5.1, followed by scenarios that introduce CO_2 emission caps and limitations on flight movements in section 5.2 and section 5.3.

5.1 Baseline

The baseline model was run without any restrictions on CO_2 emissions or the number of flight movements. This scenario was tested for all four fleet compositions, as described in section 3.4. The results are presented in table 8, where differences in performance between the fleets are primarily driven by their composition.

As expected, CO_2 emissions decrease as newer aircraft are introduced. Fleet 4, composed entirely of new aircraft, achieves the lowest emissions, with a total of 13,289,018 kg. In comparison, fleet 1, which consists of older, less efficient aircraft, emits 15,275,654 kg of CO_2. This reduction in emissions is accompanied by slight differences in profitability, connectivity and then number of flight movements. The differences in profitability, connectivity, and the number of flight movements observed between fleet 2 and fleet 3 compared to fleet 1 and fleet 4 can be attributed to the increased complexity of the model for mixed fleets. In fleet 2 and fleet 3, there are more possible combinations for the decision variable k, representing aircraft types, as these fleets consist of both older and newer aircraft. This introduces additional complexity into the optimisation problem, making it harder for the solver to reach an optimal solution within the given computational limits. The use of a solver with a 6% MIP gap means that the solver stops once the solution is within 6% of the optimal value. As a result, the differences in profitability and connectivity for mixed fleets are likely due to this gap, reflecting slight sub-optimalities in the model's solution when handling more complex fleet compositions.

Figure 1 shows the network layout under the baseline scenario. The network focuses on serving a mix of short-haul and long-haul destinations, where local flights are used to feed passengers to continental flights. This balance between short-haul and long-haul routes allows the network to optimise

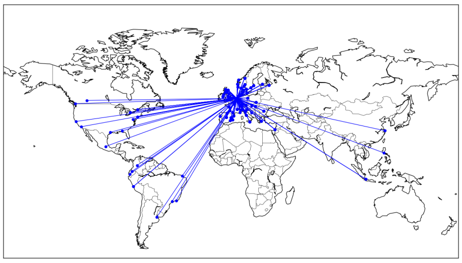

Fig. 1. Network lay-out in baseline scenario without sustainability measures

both connectivity and profitability without any operational restrictions.

In summary, the baseline scenario highlights the trade-offs between connectivity, profitability, and emissions across different fleet compositions. Fleet 4 shows to be the most environmentally efficient option, providing a clear advantage in reducing CO_2 emissions as expected.

5.2 CO_2 limitations and fleet renewal

In table 9 an overview is given of all results for the sixteen different scenarios where a limit on the allowed CO_2 emissions is imposed.

The results regarding connectivity are illustrated through the three heat maps in figures 2, 3, and 4, which visualise the connectivity scores under different fleet and CO_2 cap scenarios. As can be seen, both direct and indirect connectivity decrease with the CO_2 emissions restrictions but increase with fleet renewal. As expected, a new fleet with a low CO_2 cap leads to a high direct connectivity score, whereas an old fleet and a high CO_2 cap result in a lower direct connectivity score. The direct connectivity loss caused by capping allowable CO_2 emissions is mitigated by fleet renewal, resulting in an 8.3% increase in connections compared to the old fleet.

In figure 3, the connectivity from indirect flights involving transfers at the hub is assessed. When comparing this to the direct connectivity heat map, it can be seen that fleet renewal is also effective in mitigating the loss of indirect connectivity, with an 8.9% increase in the connectivity score for newer fleets.

Combining both direct and indirect connectivity, the total connectivity heat map offers a comprehensive view of overall network performance. As shown in figure 4, indirect connectivity plays a significant role in maintaining overall connectivity, especially when direct flights are limited by CO_2 caps. With a fully renewed fleet, high connectivity scores can be achieved despite stringent environmental constraints. For example, under the strictest CO_2 cap

TABLE 8
Profit, connectivity, CO_2 emissions, and flight movements in the baseline scenario with no sustainability restrictions for all fleet compositions

Scenario	Fleet [-]	Profit [€]	Connectivity [-]	CO_2 [kg]	Flight movements [-]
40	1	360,030,246	1296	15,275,654	414
41	2	358,454,305	1372	14,522,807	413
42	3	358,704,047	1340	13,844,492	412
43	4	360,030,246	1296	13,289,018	414

TABLE 9
Overview of scenarios with CO_2 limits

Scenario	Fleet [-]	Profit [€]	Connectivity [-]	CO_2 [kg]	Flight movements [-]	Cap [kg CO_2]
1	1	356,610,134	841	13,997,908	363	14,000,000
2	1	348,219,919	635	12,998,964	320	13,000,000
3	1	336,571,102	468	11,999,479	280	12,000,000
4	1	322,827,746	317	10,999,942	239	11,000,000
5	2	358,278,419	1,176	13,998,026	397	14,000,000
6	2	353,348,725	787	12,999,975	348	13,000,000
7	2	344,051,842	637	11,997,489	307	12,000,000
8	2	331,903,366	416	10,999,787	266	11,000,000
9	3	358,280,172	1,488	13,925,170	412	14,000,000
10	3	356,491,706	957	12,999,958	378	13,000,000
11	3	349,805,807	712	11,992,157	333	12,000,000
12	3	338,635,438	583	10,998,562	289	11,000,000
13	4	360,351,101	1,324	13,198,889	410	14,000,000
14	4	359,698,584	1,312	12,998,174	403	13,000,000
15	4	354,523,769	782	11,997,344	355	12,000,000
16	4	343,561,530	579	10,999,966	310	11,000,000

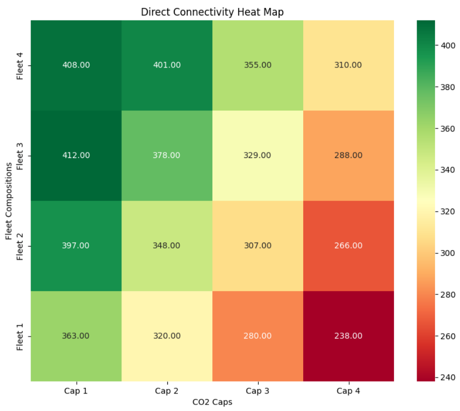

Fig. 2. Heat map of the 16 scenarios and their corresponding direct connectivity

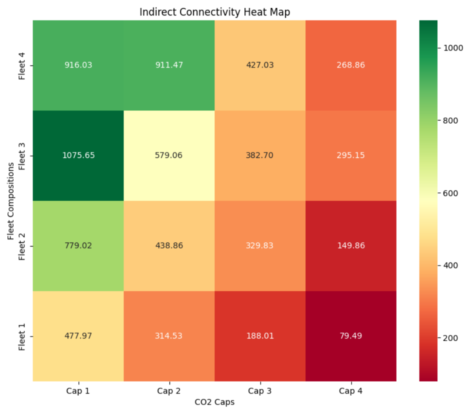

Fig. 3. Heat map of the 16 scenarios and their corresponding indirect connectivity

(Scenario 4, 11 million kg), fleet 4, which consists entirely of new aircraft, maintains a total connectivity score of 1324.03, which is a 39% reduction from the unrestricted baseline score of 1434. By comparison, fleet 1, which is composed entirely of older aircraft, sees its connectivity score drop by over 50%, from 1434 to 317.

Fleet 2 (Scenario 6, 13 million kg) and Fleet 3 (Scenario 10, 12 million kg) also show a better ability to preserve connectivity compared to Fleet 1. However, the data clearly indicates that as the proportion of new aircraft increases, so does the airline's ability to maintain its network. Fleet 4's performance illustrates the advantage of operating with modern, fuel-efficient aircraft, enabling the airline to meet environmental targets without sacrificing as much network connectivity.

Figure 5 displays CO_2 emissions on the x-axis and corresponding profits on the y-axis for each of the four fleets, across various CO_2 cap scenarios. Each fleet's performance is traced across the scenarios, showing how profitability varies with CO_2 emissions. The graph demonstrates that newer fleet configurations are better able to maintain profitability under stricter CO_2 caps. While all fleets show a decline in profit as CO_2 restrictions tighten, fleet 4 retains significantly higher connectivity and profit compared to fleet 1. Specifically, fleet 4 (Scenario 13,

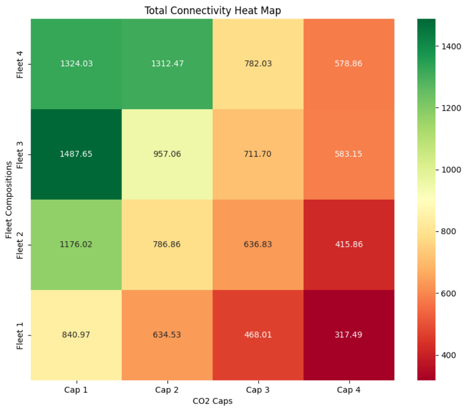

Fig. 4. Heat map of the 16 scenarios and their corresponding total connectivity

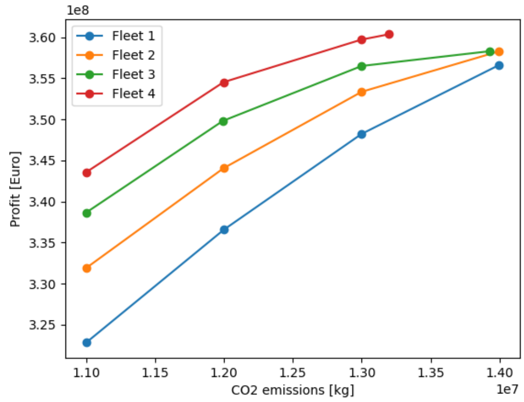

Fig. 5. CO_2 emissions and profit of the four different fleet compositions under emissions restrictions

14 million kg) shows profits of 360 million euros compared to fleet 1's 356 million euros reflecting the improved adaptability of a modernised fleet.

The CO_2 emission capping scenarios present a balanced trade-off between profit, connectivity, and CO_2 savings compared to the flight movement limitation scenarios discussed in section 5.3. Compared to the flight movement cap, CO_2 caps push airlines to make broader operational adjustments, resulting in more gradual declines in both profitability and connectivity. For instance, Scenario 4 (11 million kg of CO_2) achieves significant CO_2 savings compared to Scenario 40 (more than 15 million kg), but with a noticeable impact on profitability, which drops from 132 million euros to 124 million euros. Connectivity also decreases from 1434 to 666, showing that the CO_2 cap requires airlines to cut routes or use more efficient aircraft.

In Fleet 3, Scenario 12 results in emissions of 11 kg, down from almost 14 million kg in Scenario 42. Profitability decreases from 131 million euros to 129 million euros, and connectivity decreases from 1340

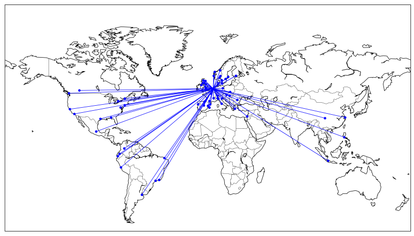

Fig. 6. Network lay-out in scenario 4: CO_2 cap of 11 million kg CO_2, old aircraft

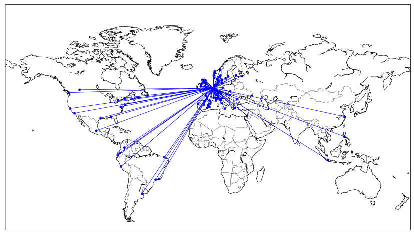

Fig. 7. Network lay-out in scenario 9: CO_2 cap of 14 million kg CO_2, 66% new aircraft

to 712. The findings suggest that CO_2 caps require airlines to make incremental changes across their operations, leading to more balanced outcomes in terms of profit and connectivity compared to the more abrupt adjustments required under flight caps.

Overall, the CO_2 emission cap strategy leads to a more flexible and sustainable approach, allowing airlines to reduce their environmental impact while balancing reductions in profitability and connectivity. Unlike flight caps, which directly limit operational capacity and more heavily impact connectivity, CO_2 caps encourage gradual operational adjustments that lead to more sustainable outcomes in the long run, while maintaining profitability of the airline.

When looking at the network lay-out of the worst scoring scenario in figure 6 and the best scoring scenario in figure 7 in terms of connectivity, it can be seen that the network is similar. The destinations reached by the airline are similar, the frequency of flying is not.

5.3 Limitations on flight movements and fleet renewal

In table 10 an overview is given of all results for the sixteen different scenarios where a limit on the number of flight movements is imposed.

Figures 9, figure 10, and figure 11 illustrate the heat maps of connectivity scores for scenarios 17 to 32, showcasing the effects of capping the number of flight movements connectivity across different fleet compositions. In figure 8 the profit and emissions for the different fleet types can be found.

TABLE 10
Overview of scenarios with a limited number of flight movements

Scenario	Fleet [-]	Profit [€]	Connectivity [-]	CO_2 [kg]	Flight movements [-]	Cap [Flights]
17	1	359,565,562	1,172	15,030,565	400	400
18	1	358,318,870	1,023	14,516,766	375	375
19	1	355,788,660	863	14,137,571	350	350
20	1	351,368,419	802	13,684,364	325	325
21	2	357,565,220	1,217	14,299,968	400	400
22	2	357,030,210	1,034	13,939,078	375	375
23	2	355,061,316	887	13,483,823	350	350
24	2	350,929,452	711	13,117,982	325	325
25	3	358,069,188	1,311	13,737,098	400	400
26	3	357,465,763	1,080	13,393,152	375	375
27	3	355,084,079	874	12,986,369	350	350
28	3	350,870,679	827	12,616,185	325	325
29	4	359,565,562	1,172	13,097,072	400	400
30	4	358,322,147	1,055	12,688,417	375	375
31	4	355,792,641	834	12,428,553	350	350
32	4	351,368,419	802	12,088,465	325	325

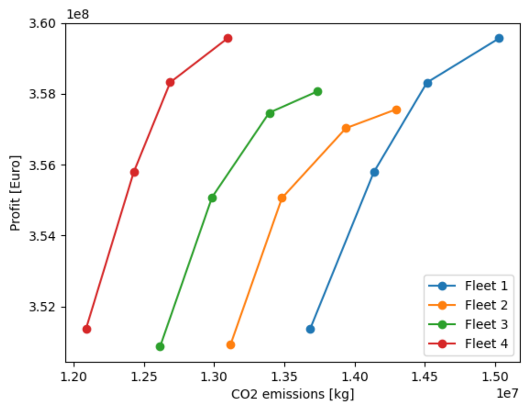

Fig. 8. CO_2 emissions and profit of the four different fleet compositions under restricted number of flight movements

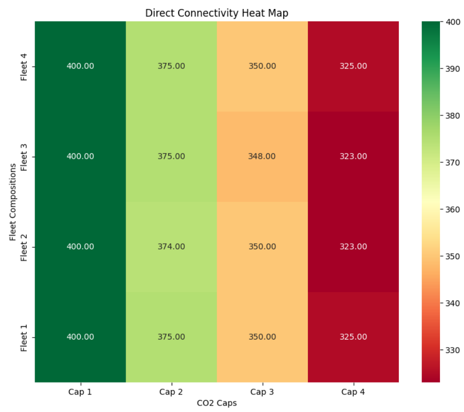

Fig. 9. Heat map of the 16 scenarios and their corresponding direct connectivity under restriction on the daily number of flights

The analysis of the flight cap scenarios demonstrates how restrictions on the number of flight movements influence emissions, profit, and connectivity. Connectivity is influenced not only by the number of destinations and frequency but also by the quality of connections passengers experience, including indirect connectivity as described in section 3.5. This dual aspect suggests that even as the number of flights decreases, it is possible to maintain or enhance overall connectivity through optimised indirect connections.

As the cap on flight movements is progressively reduced, from no cap to limits of 400, 375, 350, and finally 325 flights, emissions and profits generally decrease. This trend aligns with expectations, as fewer flights lead to lower fuel consumption, which reduces emissions, and a decreased number of flights also implies fewer opportunities for revenue generation. However, the impact on connectivity is more nuanced due to the interplay between direct and indirect connectivity. In some cases, connectivity decreases as the cap tightens, but in others, it surprisingly remains stable or even increases, suggesting that optimising indirect connectivity plays a crucial role in maintaining network performance under constrained conditions.

Starting with direct connectivity matrix in figure 9, a clear pattern is observed as flight caps are introduced. As seen, direct connectivity decreases as flight caps tighten. For fleet 4, the direct connectivity score starts at 400 with no cap and drops to 325 when the cap is set to 325 flights. This decrease is expected, reflecting the reduced number of available direct flights as constraints are imposed. In comparison, fleet 1 shows a similar decline, from 400 to 325 direct connections under the same conditions. This trend highlights the inherent limitations of operating under tighter flight constraints.

Indirect connectivity scores reveal the capacity of each fleet to leverage connections through the hub. Fleet 3 maintains the highest indirect connectivity, reflecting its ability to support passengers effectively even as direct connections decline. This demonstrates that while direct connectivity suffers under caps, the operation of indirect connections is

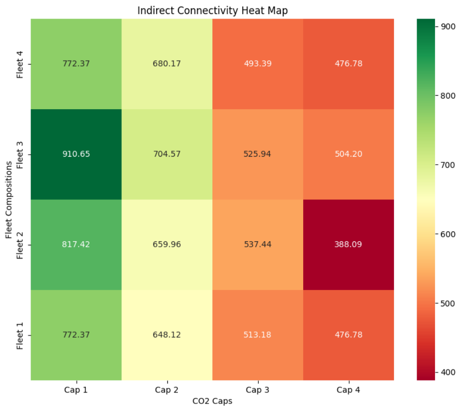

Fig. 10. Heat map of the 16 scenarios and their corresponding indirect connectivity under restriction on the daily number of flights

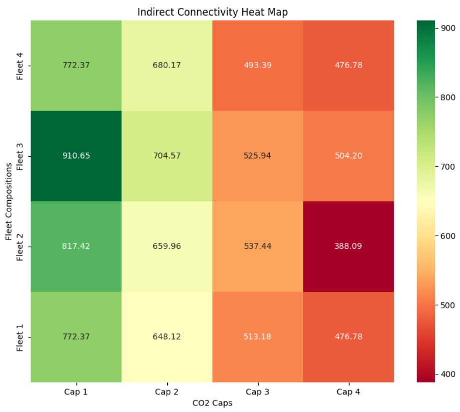

Fig. 11. Heat map of the 16 scenarios and their corresponding total connectivity under restriction on the daily number of flights

crucial for overall network performance.

In figure 10 the heat map is show of the indirect connectivity for the scenarios with a restricted number of flight movements.

The total connectivity scores illustrate that while direct connectivity diminishes with flight caps, the optimisation of indirect connectivity helps to mitigate some of the negative impacts associated with flight movement restrictions. For example, even with a reduction in direct connectivity, fleet 3 achieves a total connectivity score of 873.94 under the 350 flight cap, indicating effective use of remaining flights to serve passengers indirectly and serve more OD-pairs.

When examining emissions and profit, it is clear that emissions predictably decrease as flight caps are introduced, since fewer flights lead to lower fuel consumption. For instance, in fleet 1, the profit in Scenario 20 (325 flights) drops slightly from almost $130 million euros to $130 million euros, while CO_2 emissions reduce from 11.55 million tons to 9.38 million tons. This suggests that airlines can manage their operational costs effectively despite the limitations imposed by flight caps.

In fleet 2, Scenario 24 (325 flights) results in CO_2 emissions of 8.71 million tons compared to 11.19 million tons in Scenario 41, with a moderate profit decline from $131.60 million to $129.46 million. The relatively stable profitability indicates that airlines maintain financial stability by focusing on optimising the yield per flight and improving the utilisation of the remaining flights, even as connectivity becomes constrained.

In summary, while direct connectivity behaves as expected, decreasing with fewer flights, the ability to optimise indirect connections is crucial for maintaining overall connectivity. The interplay between profit, emissions, and connectivity underscores the need for airlines to adapt their operations strategically to navigate regulatory constraints while ensuring operational efficiency.

6 Conclusion

The analysis emphasises the crucial influence of fleet composition in minimising the impact of CO_2 emissions caps on airline connectivity. Newer and more fuel-efficient fleets are far better suited to comply with strict emissions limits while still preserving high levels of connectivity. In contrast, older fleets encounter significant operational difficulties when faced with stricter environmental regulations, which can greatly restrict the airline's ability to optimise its network. These results underline the necessity of investing in modern, efficient aircraft to adapt to ever-tightening environmental standards while maintaining operational efficiency.

The findings make it clear that fleet renewal and the implementation of sustainability measures, such as CO_2 caps, play a significant role in shaping an airline's connectivity. While older aircraft struggle under these constraints, newer, more fuel efficient aircraft allow airlines to sustain connectivity. Strategically updating the fleet not only alleviates the negative effects of sustainability initiatives but also positions the airline for enhanced overall network performance, as evidenced by improvements in the Netscan connectivity score. This underscores the essential role of modernising the fleet in securing long-term connectivity and competitiveness in a regulated industry.

When comparing the two environmental strategies, the analysis reveals that the connectivity losses resulting from restrictions on the number of flight movements cannot be offset by simply deploying newer aircraft as expected. This approach also proves to be less effective in reducing CO_2 emissions since the model tends to focus on longer flights, leading to a lower connectivity score when fleet size is limited. Consequently, if regulations on flight movements were to be enforced, the airline would be unable to mitigate connectivity losses through fleet renewal alone, contrary to expectations. However, under CO_2 emissions caps, the airline can preserve its connectivity by replacing older aircraft with more fuel-efficient models. In this scenario, a newer fleet can effectively sustain both connectivity and profitability, even within the confines of emissions regulations.

7 RECOMMENDATIONS

For further research it is recommended to do the same analysis and calculate the IATA connectivity index for the different scenarios. The main application of the NetScan air connectivity model is for competitive analysis of airline and airport networks. By contrast, the IATA air connectivity index, which evaluates air connectivity for cities, countries and regions, is designed for use by policy makers to improve air connectivity in their countries and regions with the view to unlock the potential for economic growth [14].

In this research the analysis was done for a set of 135 airports, but only current KLM destinations were considered as there was no pricing or demand information available for other airports. In order to make a better assumption of the consequences of sustainability measures on the connectivity of KLM, the possibility of serving other markets should be considered.

In light of the findings from this study, future research should consider incorporating flexibility in aircraft start locations, allowing them to begin operations from where they were left at the end of the day. This change could significantly enhance operational efficiency, as aircraft would be better positioned to optimise their routes based on demand. Allowing aircraft to start at various airports within the network could lead to a more diverse range of route offerings, ultimately increasing overall connectivity for the airline. Expanding the model to simulate a full weekly schedule would provide a more comprehensive view of airline operations, including the dynamics of overnight stays at various spokes, which would enable a more realistic representation of how airlines manage their fleets. Additionally, future iterations of the model should incorporate start-up costs associated with. These costs can impact overall profitability and should be accounted for when evaluating the financial implications of flexible start locations. Understanding the trade-offs between operational efficiency and start-up costs will provide valuable insights for decision-makers aiming to optimise their fleet operations. With advancements in computational power and algorithms, there is an opportunity to apply more sophisticated optimisation techniques to the model, facilitating the handling of larger datasets and more complex scenarios while allowing for a deeper analysis of various operational strategies.

This leads to another limitation encountered in this study was related to the data, specifically the inability to differentiate between Direct Operating Costs (DOC) and Indirect Operating Costs (IOC). Since the costs associated with aircraft not being used were not penalised, the model did not account for the financial inefficiencies of idle aircraft. In practice, unused aircraft represent a significant cost for airlines, including parking fees, maintenance, and lost revenue opportunities. Incorporating a penalty for under-utilisation in future models could provide a more accurate reflection of real-world operating conditions and help airlines make more informed decisions regarding fleet deployment and network design.

Additionally, the CO_2 emissions calculations in this study were performed using the OpenAP model, which did not accommodate the use of next-generation aircraft. This limitation meant that the potential benefits of more modern, fuel-efficient aircraft could not be fully explored. Given the rapid pace of technological advancements in aviation, incorporating newer aircraft models into future evaluations could offer more insights into how airlines can meet stricter environmental regulations while maintaining connectivity. Including next-generation aircraft in the analysis could highlight opportunities for airlines to further reduce emissions and improve overall efficiency in their networks.

REFERENCES

[1] Brandon Graver, Ph.D., Kevin Zhang, Dan Rutherford, Ph.D. CO2 emissions from commercial aviation, 2018. *The International Council on Clean Transportation*, 2019.

[2] Thirupathi Boningari, Panagiotis mirniotis. Impact of nitrogen oxides on the environment and human health: Mn-based materials for the NO_x abatement. *Current Opinion in Chemical Engineering*, 13:133–141, 2016.

[3] Bo Zou, Gurkaran Singh Buxi, Mark Hansen. Optimal 4-D Aircraft Trajectories in a Contrail-sensitive Environment. *Networks and Spatial Economics*, 16:415–446, 2013.

[4] United States Environmental Protection Agency. Health and Environmental Effects of Particulate Matter (PM). 2013.

[5] Bruno Santos. AE4423 Airline Planning and Optimization 2018/2019 Q2, lecture 1.

[6] Schiphol. Schiphol and the future - Staying in balance with the local area, 2013. 10-03-2023.

[7] N.K. Taneja, G. Burghouwt. *Transforming airlines*. Routledge, 2020.

[8] J. Benjamin. Ministerie: krimp is de enige optie om geluidsoverlast schiphol te beperken. *NRC*.

[9] A. Nandram. Minister: krimp schiphol is tijdelijk, vanaf 2027 ongelimiteerd vliegen met 'schone' vliegtuigen. *de Volkskrant*.

[10] Schiphol. Schiphol traffic review 2021.

[11] ACI EUROPE. Airport Industry Connectivity Report. 2022.

[12] Germà Bel, Xavier Fageda. Getting there fast: globalization, intercontinental flights and location of headquarters. *Journal of Economic Geography*, 8(4):471–495, 2008.

[13] Mariasole Banno and Renato Redondi. ir Connectivity and Foreign Direct Investments: Economic Effects of the Introduction of New Routes. *European Transport Review*, 6(4):355–363, 2014.

[14] IATA. Air Connectivity: Measuring the connections that drive economic growth. 2020.

[15] Jaap Bouwer, Alex Dichter, Vik Krishnan, Steve Saxon. The six secrets of profitable airlines. *McKinsey & Company*, 2022.

[16] Jim Hamill. Competitive strategies in the world airline industry. *European Management Journal*, 11(3):332–341, 1993.

[17] Renato Redondi, Paolo Malighetti, Stefano Paleari. Dehubbing of airports and their recovery patterns. *Journal of Air Transport Management*, 18(1):1–4, 2012.

[18] Council of the EU and the European Council. European Green Deal, 2022. 29-03-2023.

[19] Council of the EU and the European Council. Fit for 55, 2023. 29-03-2023.

[20] Stelios Pesmajoglou. Carbon Offsetting and Reduction Scheme for International Aviation - CORSIA. *ICAO capacity building seminar on low emissions aviation measure*, 2018.

[21] Rijksoverheid - Ministerie van Infrastructuur en Waterstaat. Verantwoord vliegen naar 2050, Luchtvaartnota 2020-2050. 2020.

[22] Jasper Faber, Stefan Grebe, Daan Juijn, Julius Király, Louis Leestemaker, Christiaan Meijer (CE Delft), Peter Frankena, Jerry Knuyt (ADECS Airinfra), Evert Windels (ADSE), Floris de Haan (Erasmus University Rottredam), Gijs van Eck, Marco Kouwenhoven (Significance), Andre van Velsen (TAKS). Impacts of a CO2 ceiling for Dutch aviation. *CE Delft for Ministry of Infrastructure and Water Management*, October 2022.

[23] Stefan Grebe, Christiaan Meijer, Julius Király, Louis Leestemaker. Updated impacts of a CO2 ceiling for Dutch aviation. *CE Delft for Ministry of Infrastructure and Water Management*, December 2022.

[24] G. Burghouwt, R. Redondi. Connectivity in Air Transport Networks, An Assessment of Models and Applications. *Journal of Transport Economics and Policy*, 47:35–53, 2013.

[25] Hayley Morphet and Claudia Bottini. Air connectivity: Why it matters and how to support growth. *Connectivity and growth - Directions of travel for airport investments*, 2014.

[26] Marius Magnus Krömer, David Topchishvili, Cornelia Schön. Sustainable airline planning and scheduling. *Journal of Cleaner Production*, 434, 2024.

[27] Lohatepanont Manoj, Barnhart Cynthia. Airline Schedule Planning: Integrated Models and Algorithms for Schedule Design and Fleet Assignment. *Transportation Science*, 38(1):19–32, 2004.

[28] Sun, Junzi and Hoekstra, Jacco M and Ellerbroek, Joost. OpenAP: An open-source aircraft performance model for air transportation studies and simulations. *Aerospace*, 7(8):104, 2020.

[29] KLM Royal Dutch Airlines. Aircraft types, 2021. April 2024.

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II

Literature Study
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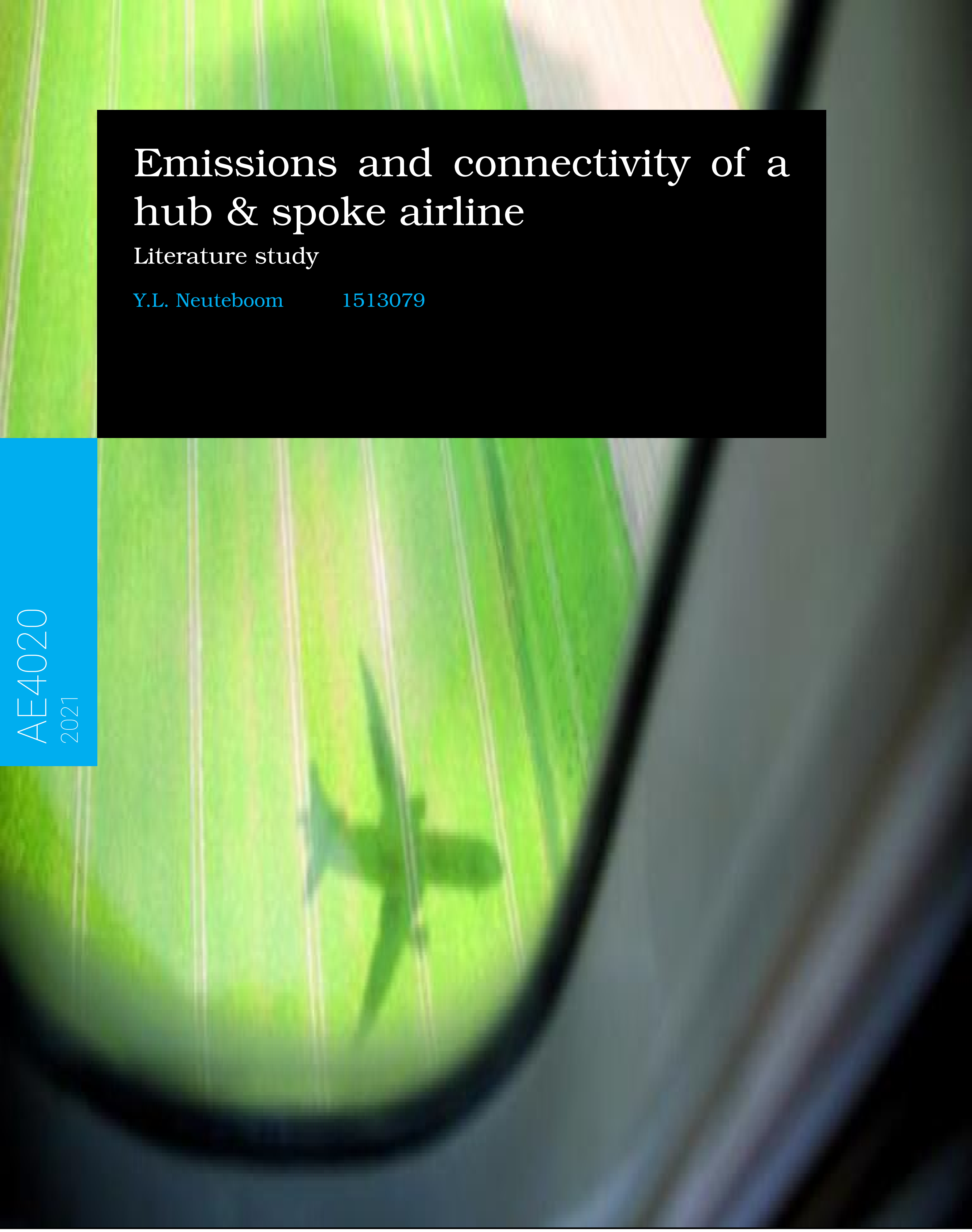

Emissions and connectivity of a hub & spoke airline

Literature study

Y.L. Neuteboom 1513079

AE4020
2021

Emissions Mitigation in Long Term Airline Planning

Literature Study - Draft

by

Y. L. Neuteboom

In Partial Fulfilment of the Requirements for the Degree of

Master of Science
in Aerospace Engineering

at the Delft University of Technology,

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Supervisors: Dr.ir. B.F. Lopes Dos Santos — Air Transport and Operations
Dr. I.C. Dedoussi — Aircraft Noise and Climate Effects

TU Delft Delft University of Technology

1 Introduction

As the interest in tackling the global warming and air quality problems has been growing worldwide, the aviation industry can not fall behind. The aviation industry was responsible for 2.5% of the global emission of CO_2 in 2018 and is expected to keep growing [10]. CO_2 is not the only problem. Contrails, nitrogen oxides and particulate matter are amongst the combustion products of aircraft engines that pose a threat to the environment and public health [60][9][62]. The airline fleet and network planning is a long-term strategic problem that is usually driven by market and financial factors [11]. However, sustainable goals are gaining increasing importance in these decisions. In line with this, new technologies and environmental policies have been proposed, but so far there is still a lot to win in aviation regarding sustainability.

Inhabitants of residential areas surrounding airports are protesting against the growth of airports due to noise and emissions nuisance. Schiphol airport in The Netherlands, the hub of KLM Royal Dutch Airlines, is situated in a densely populated area. In 2008 the capacity ceiling of the airport was set at 500,000 flight movements per annum [54]. Since 2017 Schiphol has been operating very close to this maximum capacity, while resistance of the population of Amsterdam and surrounding areas increased [39]. In the summer of 2022 the Dutch government decided that Schiphol airport has to reduce the annual number of flights by 12% to 440,000 by November 2023 [8]. However, the government proposed to allow growth from 2027 onward under the condition that the nuisance will not exceed what 440,000 annual flights cause today [37].

The shrinkage of Schiphol airport will have big consequences for KLM. The airline uses Schiphol as a hub for its operations and operates around 70% of the flight movements [53]. Airport hubbing is a practice where an airline uses a particular airport as a central connecting point for its flights. The airline schedules its flights in such a way that passengers can conveniently transfer from one flight to another at the hub airport, often resulting in shorter travel times, increased frequency of flights, and a wider range of destination options. The hub function for KLM is one of the reasons that Schiphol is ranked number one in the ACI EUROPE Airport Industry Connectivity Report of 2022 [3]. A high airport connectivity has great benefits for the areas surrounding the airport and is one of the key drivers of economic growth [20][33][22].

From KLMs perspective connectivity is a critical component of their success as well. By offering a wide range of destinations, airlines can increase their revenue by attracting more passengers who prefer to fly to their desired destination on the same airline without having to self-connect. Airlines that are able to offer unique connections and itineraries tend to outperform their less connected rivals [24]. Airlines with a strong network have a competitive advantage over their rivals, as passengers are more likely to choose an airline that offers them a more convenient and efficient route to their destination, leading to customer loyalty, repeat business and positive recommendations [26].

It is therefore necessary to research other options to decrease emissions and improve air quality around airports without having to weaken the hub function of KLM and connectivity of Schiphol Airport. This is especially important since de-hubbing of an airport is very likely to be irreversible [50]. In this work the possibilities and opportunities of using an airline planning framework to decrease aircraft emissions are researched. The goal is to find an approach that has not yet been researched and that can contribute to a future where Schiphol connects The Netherlands to the rest of the world while making sure the Amsterdam area stays a wonderful place to live.

2
The airline planning process

An airline planning framework is a crucial tool for managing an airline, which encompasses a range of tasks from long-term strategic planning to short-term operational decisions. By developing an effective planning framework, airlines can balance their goals with the impact on the environment and community, ensuring that their growth is sustainable and benefits all stakeholders involved.
To develop an airline planning framework in which the negative influences of Schiphol Airport on the environment and community around Amsterdam are compared to the connectivity of the airline, it is important to understand the airline planning process and the tools that are available. When managing an airline, a planning framework is used, which is divided in different tasks ranging from long term to short term planning. As can be seen in Figure 2.1 the long term planning corresponds to strategic decisions and the short term planning corresponds to operational decisions. This document focuses on all parts of the process in order to identify where there is a gap in literature. The figure shows that this includes network development, fleet planning and frequency planning. The fleet assignment is also considered, as the composition of the fleet has a large impact on the emissions, the ASKs and frequency on a route.
The steps in the airline planning process are interconnected and would ideally be performed at once. However, as this would enlarge the problem enormously these tasks are performed individually and iterated in order to find the best solution. In Section 2.1, Section 2.2 and Section 2.4 the network planning, fleet planning and frequency planning process are described. The other tasks in the timeline show in Figure 2.1 are beyond the scope of this work. In the last section, Section 2.6 a summary is given of this chapter.

2.1. Network development

The network development phase combines route planning and network structure. Route planning refers to the identification of origin-destination pairs that optimize profit, based on demand and revenue forecasts. This takes technical aircraft capabilities, airport availability, regulatory issues and other practical constraints into account. The choice of network structure determines how to serve the profitable Origin-Destination (OD) pairs. Currently, there are two network structure types that are widely used, Point-to-Point (P2P) and Hub-and-Spoke (H&S). A schematic version of both network types can be found in Figure 2.2 [1].

Point-to-point network

In a P2P network structure, the airline OD-pairs are connected by direct flights. This network structure is particularly profitable on high demand routes, however Low Cost Carriers (LCCs) operate purely on a P2P basis and have managed to exploit routes with a lower demand as well by cost effective operations.

Hub-and-spoke network

KLM is a H&S network carrier and operates with Schiphol Amsterdam Airport as its hub. A H&S network operates OD-pairs with flight connecting at the hub. This allows passengers with different origins and destinations to board the same flight and makes routes with a lower demand profitable. To facilitate fast transfers,

[1] https://transportgeography.org/contents/chapter2/geography-of-transportation-networks/point-to-point-versus-hub-and-spoke-network/

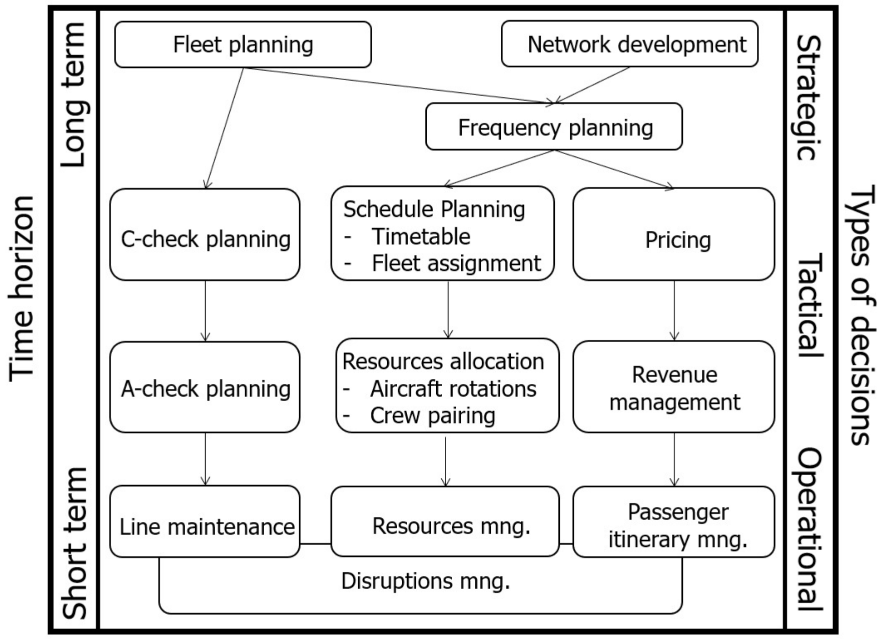

Figure 2.1: Airline planning framework timeline [11]

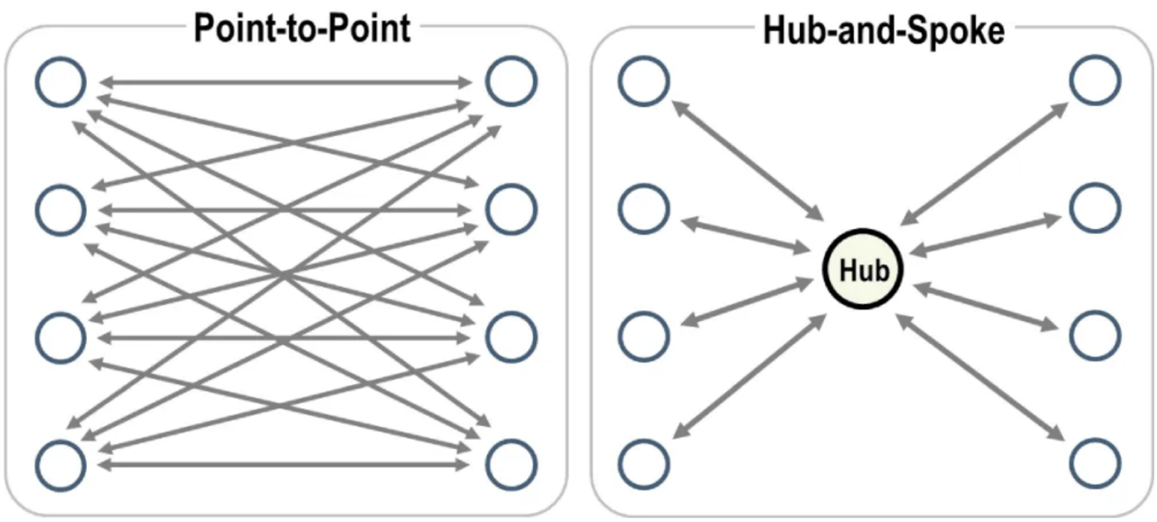

Figure 2.2: Schematic representations of a P2P network (left) and a H&S network (right)

most hub airports work with connecting banks or waves. Passengers and cargo from the origins arrive at the hub at the start of the wave, have time to transfer to the connecting flight, and depart to their destinations at the end of the wave. Even though this ensures quick transfers, there are downsides to this approach. During the waves, the hub runs on peak capacity, which congestion and its extra emissions as a result, while only little capacity is used outside of the waves. To use resources more evenly some airlines have introduced the rolling hub, at which arrivals and departure are spread over the day, but with a high probability of longer transfer times.

Katz and Garrow (2014) quantified the revenue and operation impacts of depeaking hubs in the U.S, using difference-in-difference methods. In this research it was concluded that for the five U.S. hubs, the depeaking improved operations but had a mostly negative impact on the revenue per ASK. However, the cost saved by the improved operations in the rolling hub was not mentioned [16]. Brueckner and Lin (2016) modelled a rolling hub to trade-off convenient flight connections with airport congestion. Layover costs were attributed to longer transfer times and it was concluded that in case of a monopoly hub carrier the flights were more concentrated if the layover cost is high, and less concentrated for low layover cost. When fringe carriers were included, the hub carrier tended to concentrate its flights and in case of two hub carriers, the outcome resembled the monopoly case [27]. The link between hub operations and emissions at an airport is made by Levine and Gao (2007). A queuing model for aircraft waiting to depart was made and the emissions associated to aircraft taxi-out over the course of a day at Newark Liberty International Airport were computed for different scenarios and it was concluded that congestion mitigation and fleet restructuring could lead to significant decrease in emissions at the airport [12].

The missing link in literature is the connectivity loss of an airport or airline when changing hub operations to decrease emissions. Emission mitigation solutions have been researched extensively and the benefits of certain strategies for the environment can not be denied. However, the connectivity of large hub airports as Schiphol airport should be included in research.

2.2. Fleet planning

Together with the network development, fleet planning is the most long term and strategic step in the process. During fleet planning is decided what type and how many aircraft should be acquired to serve the network. The ultimate goal is to match required Available Seat Kilometres (ASKs) and produced ASKs. As there are many uncertainties regarding demand and revenue forecasts as well as regulations and politics, a solid fleet plan should be flexible and suitable for multiple scenarios. Belobaba et al. described two fleet planning approaches; the top-down approach and the bottom-up approach [46].

Top-down approach

The top-down or macro fleet planning approach is based on many assumptions regarding demand forecasts, future aircraft specifications and financial data. All these assumptions are used to estimate financial impact of possible fleet acquisition scenarios. Even though this approach offers a rough estimate at best, this manner of working is widely adopted in the airline industry.

Bottom-up approach

The bottom-up or macro approach is a more refined strategy. A model is made, taking into account more details and system complexities. While the top-down approach accepts general data, the bottom-up approach aims at a more realistic representation of the future. However, with the high level of uncertainties, more detail in the models does not necessarily mean a more realistic model. This approach requires more computational time and modelling effort, while still giving highly uncertain results, hence the top-down approach is preferred in most cases.

Fleet planning and emissions

The next generation aircraft that are taken into service now are 20% more fuel efficient than their predecessors, but more fuel efficient aircraft emit more NO_x, creating a trade-off between fuel efficiency, including CO_2 emission and NO_x emission [38]. The early retirement of the older aircraft of a fleet comes at a cost. Rosskopf et al. (2014) used a multi-objective linear programming model to optimise the fleet composition, fleet development and fleet employment of an airline, trading off environment and economical optimal fleet plan. In their case study for a major European airline the model showed that the airline had to deviate 3% from their economical optimum to improve their environmental foot print by 6% [36]. Dray et al. (2014) discuss a carbon tax which is used to fund fleet renewal subsidies and predicts a 34% decrease in CO_2 emissions with this policy aiming at retirement of aircraft over 20 years old [29].

Grampella et al. (2016) did an econometric analysis of 1500 aircraft-engine combinations and concluded that aircraft age is the the main determinant of environmental cost and that medium size aircraft have a better environmental performance per ASK than both small and large aircraft. Only for very low demand, small aircraft are the better choice [34]. Ekici et al. (2023) did more research into engine-aircraft pairing. This study suggests that airlines and policy makers should consider specific aircraft-engine parings in their calculations of fuel consumption and emissions, instead of directly using the fuel consumption given by the engine manufacturers [55].

2.3. Fleet assignment

The fleet assignment problem (FAP) involves selecting the appropriate types of aircraft, each with varying capacities, for scheduled flights. This decision takes into account the availability of planes, their capabilities, operating costs, and potential revenue. Because fleet assignment directly affects an airline's revenue, it plays a critical role in the broader scheduling process. However, with the vast number of daily flights and the interconnections of the FAP with other airline operations, finding the best solution has always been a difficult challenge for airlines [?]. Abara (1987) addressed the FAP by developing and solving an integer linear programming model that allows multiple fleets to be assigned to a flight schedule at the same time. The model's objective can vary, focusing on maximising profit, minimising costs, or optimising the use of specific fleet types. This approach thereafter was used by several departments at American Airlines to support their fleet planning and schedule development efforts [?]. Understanding that flexibility in scheduled flight departure times can lead to better flight connections and more cost-efficient fleet assignments, Rexing et al. (1997) introduced a generalised fleet assignment model that simultaneously assigns aircraft types to flights and schedules departure times. This model, which is a straightforward extension of standard fleet assignment models, allocates a time window to each flight and divides it into intervals, enabling the optimisation of departure times [?]. In chapter 4 one the most widely used connectivity scaling system, Netscan connectivity, relies heavily on the scheduling of the connections, which makes a time slot based scheduling tool a viable option for future research.

More recently, Xu et al. (2024) developed an integrated mixed-integer optimisation model that simultaneously determines flight schedules, fleet assignments, and average airfares, since airline profits are largely driven by how well flight schedules align with passenger demand and available fleet resources. The model accounts for passenger preferences by incorporating a prospect theory-adjusted, nested multinomial logit model to predict market share. To simulate competitive behaviour, the model is set within a differentiated Bertrand game framework, where each airline optimises its strategy based on the market share outcomes. To tackle the complexity of this integrated problem, we introduce a hybrid algorithm that efficiently combines stabilised column generation with a large neighbourhood search technique [?].

2.4. Frequency planning

In the frequency planning stage it is investigated how often an airline should fly on the routes determined in the network development stage. This is closely connected to fleet planning, since aircraft with a higher seat capacity are able to transfer more passengers per flight than smaller aircraft and are able to serve the same demand with a lower flight frequency. However, flying a certain route at a higher frequency with smaller aircraft can be beneficial. Givoni and Rietveld (2010) researched the environmental implications of the choice of aircraft size and found that increasing aircraft size and adjusting the frequency accordingly to allow for the same number of available seats lead to more local pollution, but decreased the global impact [30]. This research was limited to the replacement of Airbus A320-200 and Airbus A319-100, considered 'small' aircraft, with Boeing 747-400 and A330-300, considered 'large' aircraft. In the case of KLM the fleet is more extensive and varied. KLMs ambition to accelerate its fleet renewal and the availability of more modern and more energy efficient aircraft could lead to different results.

2.5. Airline routing

Airline routing refers to the process of determining the specific paths or routes that aircraft will follow to connect different airports within an airline's network. This involves planning and organising flights so that they efficiently link various destinations, considering factors like fuel efficiency, airspace regulations, weather conditions, and overall operational costs. An important aspect of airline routing is the design of a schedule that is minimally influenced by propagated delays. Yan & Kung (2014) presents a robust optimisation approach to reduce total propagated delays in aircraft routing by minimising the worst-case delays, rather than relying on expected delay distributions. The model accounts for correlations in delays, like those caused by weather, which are often overlooked by other methods. Testing with real and simulated data shows that this approach generally outperforms traditional methods by reducing average delays, volatility, and extreme delays [**?**]. One of the trend is in operations research literature is the integrated approach of multiple steps in the airline planning process. Ben Ahmed et al. (2022) propose an integrated fleet assignment, aircraft routing, and crew pairing algorithm that proved efficient when doing computational experiments on a real airline.

2.6. Summary & conclusions

To develop an airline planning framework in which the negative influence on the environment is minimised, it is important to understand the airline planning process. When managing an airline, a planning framework is used, which is divided in different tasks ranging from long term to short term planning. This document only considers long term airline planning. This is where strategic decisions should be made regarding fleet planning, network development and frequency planning. The route planning problem addresses the question from which origin to which destination to fly while making profit based on demand and revenue forecasts. A choice must be made between operating an H&S or a P2P network. Together with the network development, fleet planning is the most long term and strategic step in the process. During fleet planning it is decided what type and how many aircraft should be acquired to serve the network. A top-down approach based on many assumptions regarding the future is most widely used. In the frequency planning stage it is investigated how often an airline should fly on the routes determined in the network development stage. As the goal of this research is to find an approach to investigate the impact of sustainability measures on the connectivity of the airline, the focus should be on route and frequency planning. The different fleet planning approaches are less relevant for the future of this study, since the replacement of older aircraft with newer, more energy efficient ones will be considered as one of the sustainability measures.

3

Aviation and airport emissions

Commercial flights have become an essential part of modern society, but they have a significant impact on the environment, particularly on radiative forcing, aviation emissions, and noise. As a result, regulations have been implemented to mitigate these negative impacts and promote sustainable aviation. When looking for a solution for the emissions problem, a better understanding of the elements that leave the engine is vital. The different combustion products of emissions all have a different influences on the processes in the atmosphere. In Section 3.1 the scientific background of the greenhouse effect, Radiative Forcing (RF), is discussed and in Section 3.2 the different combustion products and their influence on RF are discussed. In section 3.4 the most important regulatory instances are described and in section 3.5 a promising software package for emissions calculation is discussed. The chapter closes off with a summary in Section 3.6.

3.1. Radiative forcing

RF is the scientific explanation for the more commonly known greenhouse effect. It describes the change in energy flux in the atmosphere of a planet and can be caused by natural and anthropogenic factors. Natural factors that influence RF are changes in solar irradiance, changes in albedo and natural emission of atmospheric gasses. Anthropogenic RF is mostly caused by emission of atmospheric gasses due to burning of fossil fuels, which is still the main manner of propulsion in aviation. There is positive RF when the Earth receives more energy from the Sun than it emits, while in the opposite case there is negative RF. Positive RF increases the Earth's temperature, this phenomenon is known as global warming. A Radiative Forcing Index (RFI) is the RF of an emissions component with respect to that of CO_2. In Figure 3.1 can be seen how different greenhouse gasses relate to CO_2 in terms of radiative forcing. As can be seen in the figure, CO_2, NO_x and contrails had the highest contribution to RF up to the year 2005. In many documents the Global Warming Potential (GWP) is used as a climate change metric, which is defined as the cumulative radiative forcing of one kilogram of emitted gas relative to one kilogram of reference gas [14]. The reference gas is almost always CO_2, hence the RFI and GWP are comparable measures of RF.

3.2. Aviation emissions

As the commercial airline industry is growing rapidly, the corresponding emissions due to fuel burning increase as well. In 2018 the total CO_2 emissions from all commercial operations was estimated to be 918 metric tons, which is 2.5% of global emission of CO_2 from fossil fuel burning and an increase of 32% compared to 2013 [10]. The increase in fuel efficiency has been approximately 1% over the pas few years, and this is expected to continue initially, but is expected to become increasingly smaller in the long term future [35]. Aircraft emissions are similar to the combustion of petroleum products in other sectors. However, since a significant proportion is emitted at high altitude, the global impact of aviation emissions contributes to about 3.5% of RF, which was discussed in Section 3.1 according to ICAO[1]. Besides CO_2, other relevant products of aircraft fuel combustion are nitric oxides (NO_x), water vapour causing contrails, sulphur oxides (SO_x) hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM), which are discussed below. An overview of all emissions and their influence on atmospheric processes can be found in Figure 3.2.

[1] https://www.icao.int/environmental-protection/Pages/aircraft-engine-emissions.aspx

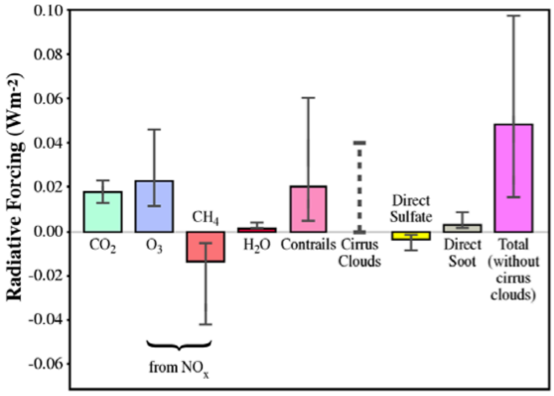

Figure 3.1: Effect of historical aviation emissions on the heat trapping ability of the atmosphere [14]

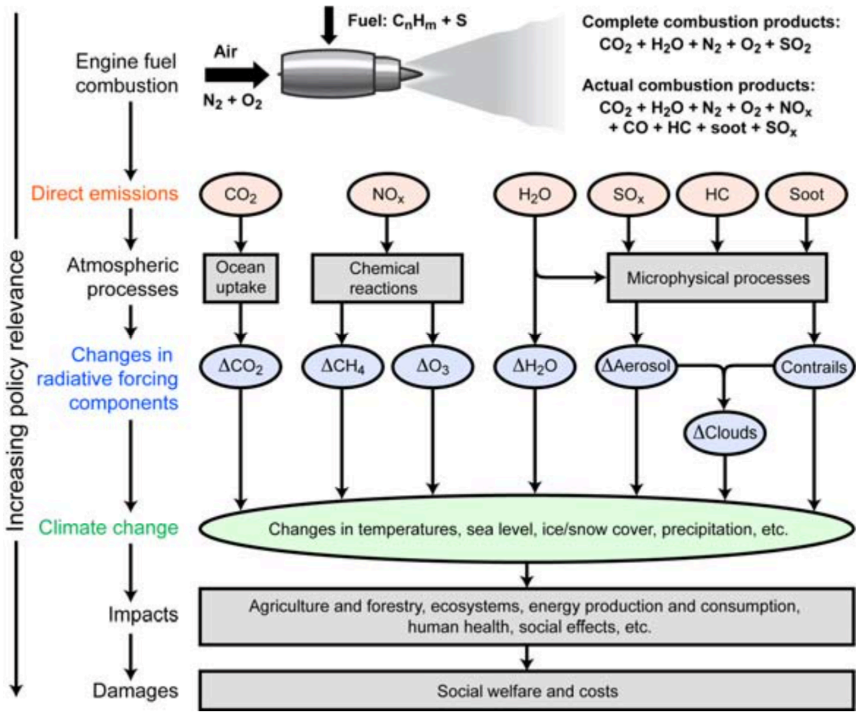

Figure 3.2: Aircraft emissions and their chain of influence [13]

Carbon dioxide

Carbon dioxide (CO_2) is one of most well known greenhouse gasses. Greenhouse gasses prevent heat from escaping into space and keep the atmosphere nice and warm. Even thought this effect is the reason human life can be sustained on Earth, excessive exhaust of greenhouse gasses disrupts the balance and causes global warming.

Nitrogen oxides

Nitrogen oxides (NO_x) are products of high-temperature combustion processes have negative effects on human health, the environment and the ecosystems [60]. NO_x is considered the third most important greenhouse gas, next to CO_2 and methane, and contributes to RF. However it plays also a role in ozone layer depletion [49], and ozone is a greenhouse gas as well. NO_x emissions from air transportation increase ozone, causing positive RF, and decrease methane, causing negative RF [5]. The reduction of methane in the atmosphere is only partially counteracting the RF from the ozone layer depletion, hence NO_x is considered to cause positive RF and is one of the combustion products of which the amount of emission should be reduced. The local effects of NO_x on the environment is on of the drivers of the desired reduction of the number of flight movements at Schiphol.

Condensation trails

Condensation trails or contrails are the line-shaped clouds one sees in the wake of an aircraft and are caused by the condensation of water in the aircraft engine exhaust in combination with the low temperatures at cruising altitude. Contrails consist mainly of ice crystals. In the same manner as natural clouds, contrails contribute to RF by preventing the radiation emitted by Earth from escaping into space and increasing the amount of solar radiation reflected. It is complicated to estimate the total effect of contrails on global warming, but it has been concluded that the climate impact of contrails on climate change is significant [9].

Particulate matter

PM includes all emitted particles with an aerodynamic diameter of 10 micrometers or smaller, which can be any mixture of components. $PM_{2.5}$ is used for particles with an aerodynamic diameter of 2.5 micrometers or less. These smaller particles can be connected with health problems, such as lung disease, hearth attacks and strokes [62][15]. PM plays a role in RF as well, since it influences the formation of contrails.

3.3. Emissions at airports

The emissions of an airport can be split up in multiple contributions. Loo et al. (2014) investigated the emissions of hub airports, looking at airport based activities, airspace based activities ant flight based activities. In this study Hong Kong International Airport, an international hub, and Athens International Airport, a national hub were used in a case study. It was found that hub airports have low CO_2efficiency at airport and airspace level and more efficiency at flight level, due to different aircraft capacity and load factor [7]. CO_2 emission can also be split in contributions from passengers arriving by car, airport terminal activities, LTO-cycles and handling vehicles as proposed in Postorino and Mentecchini (2014). These contributions are estimated and combined to find the Unit Carbon Footprint (UCF) index of the airport, as proposed in Postorino and Mentecchini (2014) [31]. Morrell and Lu (2007) compared the environmental cost of two patterns of service: hub-to-hub and hub by-pass, both operated by network carrier. The noise and emissions social cost impact of the hub by-pass service was significantly lower, which indicates that hub-and-spoke networks have increased environmental impact due to hubbing activities [47].

Schiphol airport has been CO_2 neutral since 2012, aims to be emission free in 2030 and to be energy producing in 2050 [21]. This makes Schiphol one of the most sustainable airports worldwide, hence the emission problems connected to the airport are caused by the actual air traffic.

3.4. Regulations

The relevance of the different sustainability measures in the research will be partially determined by the regulations and goals that are imposed on airlines by national and international governments and organisations.

European green deal

The European Green Deal is a comprehensive plan to make the European Union's economy sustainable and achieve climate neutrality by 2050. It includes a wide range of policies and initiatives to reduce greenhouse gas emissions, increase the use of renewable energy, and promote sustainable agriculture and forestry. The European Green Deal also aims to create a circular economy and protect biodiversity. One of the key initiatives under the European Green Deal is Fit for 55. This is a package of legislative proposals that aims to reduce the EU's greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. The Fit for 55 package includes a number of measures that are relevant for aviation. These are the EU Emissions Trading System (EU ETS) and promotion of the use of sustainable aviation fuels (SAFs), with the aim of increasing the share of SAFs in aviation fuel to 2% by 2025 and 63% by 2050 [42][43].

CORSIA

The International Cival Aviation Organisation adopted the emissions mitigation framework Carbon Offsetting and Reduction Scheme from International Aviation (CORSIA). CORSIA supports ICAO's goal to achieve carbon neutral growth from 2020. In 2021 the pilot phase of CORSIA started and in 2027 CORSIA aims to make participation mandatory for ICAO member states [58]. ICAO has many colourful leaflets and brochures with next to no information on how they will achieve these goals, so I need to find some more information on this.

Dutch civil aviation policy memorandum

The civil aviation policy memorandum contains the aim to limit CO_2 emissions of Dutch aviation to 2005-levels by 2030, reduce them by 50%, relative to 2005, by 2050 and to zero by 2070. To reinforce these goals, the government has proposed a CO_2 emission ceiling for the international aviation sector in The Netherlands. This gives a clear framework for the sector to grow in a green manner [51].

CE Delft (2023) did an assessment following the announcement of the CO_2 ceiling investigating the implications of the measure. Multiple scenarios were investigated taking into account measures from the European Fit for 55 proposals, national climate policy and socio-economic development, but also the more recent government announcement regarding the capacity reduction at Schiphol. CE Delft identified three main policy framework options, namely CO_2 ceiling for airports, for fuel suppliers or for airports. The study concluded that without government action, the Dutch CO_2 emissions from aviation would exceed the targets in most scenarios [25][57]. The effect on the connectivity of Schiphol and airlines operating from Schiphol was not taken into account in this research.

3.5. Emissions simulations software

The most state-of-the-art emissions software is OPenAP. OpenAP is an open-source aircraft performance model designed to offer a standardised, accessible tool for analysing and modelling aircraft performance. It serves a variety of aviation-related research and practical applications, including trajectory prediction, fuel consumption estimation, emissions modelling, and air traffic management research. The open-source nature of OpenAP is one of its primary strengths, as it allows users to freely access, modify, and distribute the software. This openness fosters collaboration and transparency, enabling researchers, developers, and practitioners to adapt the model to specific needs and contribute improvements. OpenAP provides detailed performance modelling for various aircraft phases, including climb, cruise, and descent. It uses aerodynamic and engine performance data to simulate aircraft behaviour under different conditions, such as varying weights, speeds, altitudes, and weather factors. The model relies on publicly available data sources, including aircraft manufacturer specifications and flight data records, ensuring that its simulations are grounded in real-world metrics. Overall, OpenAP offers a valuable solution for aircraft performance modelling, providing accurate simulations and fostering innovation in aviation through its open-source framework [59].

3.6. Summary & conclusions

As the commercial airline industry is growing rapidly, the corresponding emissions due to fuel burning increase as well. Aircraft emissions are similar to the combustion of petroleum products in other sectors. However, since a significant proportion is emitted at high altitude, the global impact of aviation emissions contributes to about 3.5% of RF. RF is the scientific explanation for the more commonly known greenhouse effect. Anthropogenic RF is mostly caused by emission of atmospheric gasses due to burning of fossil fuels.

There is positive RF when the Earth receives more energy from the Sun than it emits, while in the opposite case there is negative RF. Positive RF increases the Earth's temperature, this phenomenon is known as global warming. CO_2 is one of most well known greenhouse gasses. Greenhouse gasses prevent heat from escaping into space and keep the atmosphere nice and warm. Even thought this effect is the reason human life can be sustained on Earth, excessive exhaust of greenhouse gasses disrupts the balance and causes global warming. NO_x is considered the third most important greenhouse gas, next to CO_2 and methane, and contributes to RF, however it plays also a role in ozone layer depletion. Condensation trails or contrails are the line-shaped clouds one sees in the wake of an aircraft. In the same manner as natural clouds, contrails contribute to RF by preventing the radiation emitted by Earth from escaping into space and increasing the amount of solar radiation reflected. PM includes all emitted particles with an aerodynamic diameter of 10 micrometers or smaller, which can be any mixture of components. $PM_{2.5}$ is used for particulates with an aerodynamic diameter of 2.5 micrometers or less. PM plays a role in RF as well. When the environmental impact of the airline industry is analysed, different emission components and their effect on the RF and global warming should be taken into account. In most regulatory documents, CO_2 emission is seen as the most harmful combustion product and the leading cause of global warming. This is why the from literature can be concluded that in continuation of this project, CO_2 should be the reference gas when simulating emissions. The open sources software package OpenAP is the best fit for estimating CO_2 emissions from a simulated airline network.

4
Connectivity

Connectivity is generally defined as the degree to which nodes in a network are connected to each other [19]. In airline literature the have been many different ways to define the connectivity of airlines and airports.

4.1. Connectivity of an airport

Connectivity can be divided in different types of connectivity: Direct connectivity, indirect connectivity and hub connectivity. Direct connectivity refers to a direct flight from the origin of the passenger to the destination of the passenger. Indirect connectivity includes a layover between the OD pair. Burghouwt (2017) states that hub-connectivity can be split up in onward/beyond an hub/behind. The first indicates the concerned airport is the origin of passengers, which intend to travel beyond the flight leg. The latter means that the investigated airport is the hub and is not part of an OD pair. This is illustrated in Figure 4.1 [17].

The connectivity of an airport has been modelled in different ways, taking into account variables as number of direct and indirect connections. However, there are many more variables that could be taken into account when defining the connectivity of an airport of airline. Burghouwt mentions the following determinants: size and strength of local OD market, presence of an airline hub operation, airport and airspace capacity, airport visit costs, airport service levels and market access. He concludes that we can enhance the connectivity of an airport by investments in landside accessibility, ensuring availability of airport and airspace capacity, influencing the type of infrastructure available to airlines, economic regulation of airport charges, adjusting government fees and taxes, establishing a transparent secondary slot market, air transport liberalisation, imposing PSO's and traffic distribution rules. However, it can be argued that governments and policy makers should be hesitant when using these tools to directly influence the market. A better way to about is by creating favourable conditions for the airlines to develop their network.

To find ways to keep connectivity and hub function of an airport, the measurement and qualification of the connectivity is of importance. As mentioned above, many factors are influencing connectivity and for most case studies some are more important than others. Doganis and Dennis (1989) used the number of direct and indirect connections with constraints for minimum and maximum transfer times to determine a so called connectivity ratio [48]. Dennis introduced the routing factor, which is defined as the ratio of actual flight time or distance from origin to destination to the time of distance of a direct flight [40] [41]. Burghouwt and De Wit (2004) proposed the WNX or weighted number of connections index to evaluate airline flight schedule effects [18]. This index connected the methods of Bootsma (1997) and Veldhuis (1997), who respectively defined standard maximum connecting times for different types of connections and defined connectivity based on the attractiveness of a connection [45] [23]. Veldhuis states that the attractiveness of a connection depends on waiting time at the hub, routing factor, perception of waiting time vs. in-flight time, fares, loyalty programs of airlines and services at the airport. Veldhuis' approach is more widely known as the Netscan model and was used in the ACI EUROPE Airport Industry Connectivity Report mentioned in the Introduction [3]. Danesi (2006) developed the weighted connectivity ratio, which has the structure of Dennis and Doganis connectivity ratio, but includes in addition to the spatial connectivity the temporal characteristics of a flight schedule [2]. Budde et al. (2008) borrowed a pattern recognition software originally developed for behavioural studies and used it to observe departures and arrivals as events and recognise the pattern of possible connections [1].

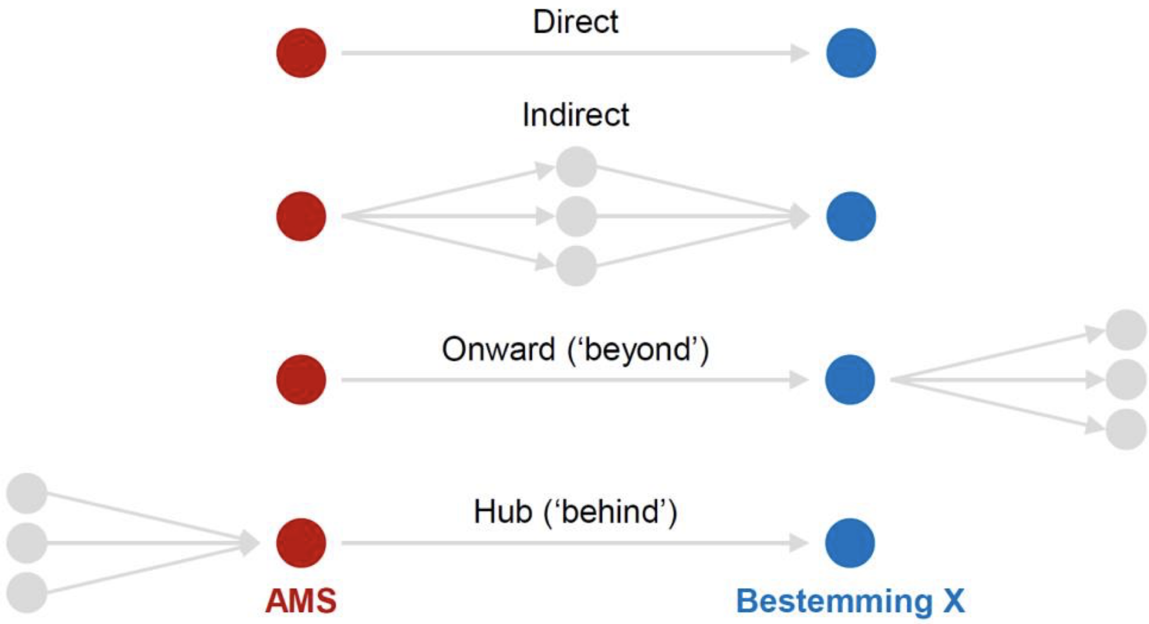

Figure 4.1: Four types of connectivity

4.2. Connectivity of a network

Malighetti et al. (2008), focused on the connectivity of a network and analysed the European airport network by looking at the shortest path from origin to destination. The shortest path being the route with the minimum number of steps from origin to destination, the average number of steps to reach any other airport in the network or the quickest path involving the lowest travel time from origin to destination [44]. Shaw and Ivy (1994) used the same methodology to examine the effect of airline mergers on the connectivity of a network [56]. Paleari et al. (2008) did a shortest path approach with travel time, the sum of in-flight time and waiting time at intermediate airports, as the governing characteristic [52].

4.3. Connectivity of an airline

Connectivity for an airline refers to the number and variety of destinations that it can offer to its customers through its own network and partnerships with other airlines.

A well-connected airline will have a wide range of flights to destinations all over the world, allowing passengers to easily travel from one city to another without having to make multiple bookings with different airlines. This can be achieved through a combination of direct flights, codeshare agreements with other airlines, and interline agreements, which allow passengers to connect between flights on different airlines with a single ticket.

Airlines with good connectivity can offer customers more convenience and flexibility, as well as the ability to earn and redeem frequent flyer miles across a broader network. It can also be beneficial for airlines to increase their connectivity to capture a larger market share and compete with other airlines that have similar networks.

4.4. Connectivity, noise and emissions

Looking at the connection between the connectivity of airports and the noise and emission problems in areas surround airports, Postorino and Mantecchini (2019) developed a quantative measure linking airport connectivity to environmental impact [32]. This so called Viable Connectivity Index (VCI) compares the positive effects of increased connectivity at an airport discussed in Section **??** with the negative carbon and noise effects associated with an increased number of flight movements. The relation between these effects as used in this study can be found in Figure 4.2. The connectivity used is an index of served destinations, frequency, passengers and GDP of the country of destination. CO_2 emission from passengers arriving by car, airport

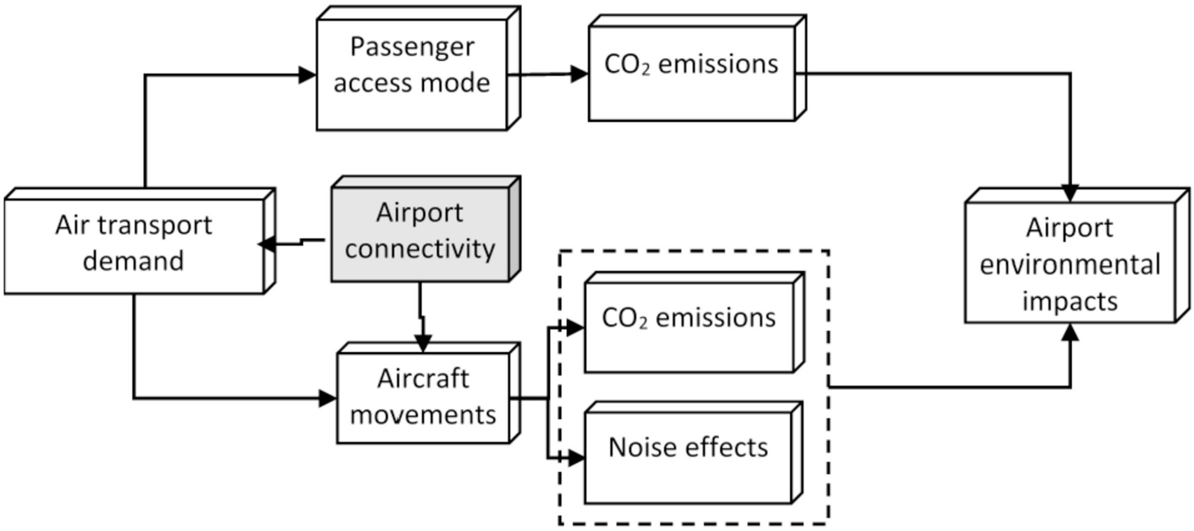

Figure 4.2: Relation between carbon and noise effects and connectivity [32]

terminal activities, LTO-cycles and handling vehicles are estimated and combined to find the Unit Carbon Footprint (UCF) index of the airport, as proposed in Postorino and Mentecchini (2014) [31]. The VCI was proven to be a useful tool, especially for smaller airports as test case Bologna Airport, to determine if growth scenarios are acceptable.
To save operating expenses while minimising the disruption to overall route network connectivity, an airline is more likely to cut routes involving endpoint airports that have low centrality values. [6]. The concept of centrality is closely linked to connectivity and is described by Cheung et al. (2020) as the importance of an airport within a transport network and the potential at which an airport is passed or by-passed when connecting passengers from an origin to a destination [61].

4.5. Summary & conclusions

In this chapter, we explored the concept of connectivity in the context of aviation networks, focusing on airports, networks, and airlines. Connectivity refers to the degree to which nodes in a network are connected to each other, and it plays a crucial role in shaping the accessibility and efficiency of air transportation systems. There are various types of connectivity found in literature, including direct, indirect, and hub connectivity. Direct connectivity involves non-stop flights between origin and destination airports, while indirect connectivity includes layovers. Hub connectivity refers to the role of airports as hubs for connecting flights, either as origin or intermediate points in a journey. There are various indices and ratios used to measure and quantify connectivity at airports and within networks, taking into account factors such as the number of connections, flight times, and the attractiveness of connections. The Netscan connectivity model is most widely acknowledged as a solid measure of connectivity. The relationship between airport connectivity and environmental impacts, such as noise and emissions is especially important for this research. The Viable Connectivity Index (VCI) was introduced as a tool to assess the trade-off between increased connectivity and environmental concerns, providing valuable insights for airport planning and management. There is no similar research available regarding the relationship between airline connectivity and emissions.

5 Conclusion

Based on the available literature, it can be concluded that there is a lack of research on the impact of environmental measures on the connectivity of H&S airlines. Despite the importance of these factors in the aviation industry, little attention has been paid to understanding the relationship between environmental measures and connectivity in this context. Therefore, further research is needed to address this gap in knowledge and inform future policy decisions related to sustainable aviation. Questions arise regarding scenarios with caps on CO_2 emission, or a ceiling on the number of flights. What happens to the network and the hub function of KLM when these hard hard limits will be enforced? Can these changes be anticipated by accelerated renewal of the fleet or the use of SAFs? Is it an option to fly with aircraft with a higher capacity on a lower frequency to maintain connectivity, serve demand and reduce emissions?
The importance of connectivity of airports and airlines is widely recognised in literature, but it is measured in many different ways. Most models are based on the number of destinations, the travel time and number of transfers. The models mostly differ in the number of characteristics of the destination airport they take into account. The Netscan Air Connectivity Measure is widely used for competitive analysis of airlines and airports and is similar to the IATA Air Connectivity Index, both focusing on quality of direct and indirect connections. Environmental measures are proposed, for example fewer flights and fleet renewal. This would leads to changes in the parameters of the network, that leads to changes in the connectivity. This literature research can be seen as the start of a project where simulating the network of KLM within the bounds of multiple sustainability measures could give more insight in the effect of these measures on the connectivity and could even lead to conclusions about trading off connectivity with CO_2 and the monetary costs of sustainable air traffic.

III

Supporting work

1

Verification & validation

Ensuring the reliability of any optimisation model is essential, especially when the results have real-world implications, such as in airline fleet and network planning. Verification and validation are crucial steps in building confidence that the model behaves as intended and produces meaningful outputs. These steps help to ensure that the model isn't just a collection of equations and constraints, but a true representation of the system it is meant to optimise. In this appendix the methods used to verify and validate the model developed in this research are discussed. First the verification of the model is described, followed by the validation. In the last section of the appendix the behaviour of the model is analysed.

Verification of the model

Verification is the process of making sure the model works as designed, checking the logic and implementation to catch errors early on. It involves rigorous testing to ensure that the code and mathematical formulations are consistent with the intended design. This step is critical in preventing potential mistakes that could compromise the results.

Three-airport simplified model tests

To verify the model, a simplified three-airport scenario was developed as can be seen in figure 1.1, allowing for a more controlled environment to test the core components of the optimisation framework. This smaller-scale model includes one hub airport and two non-hub airports to closely observe the model's behaviour and ensure that it adheres to the expected constraints and logic. By focusing on this manageable scenario, it can be systematically verified that the aircraft movement constraints and scheduling logic function correctly before scaling up to more complex scenarios. This step is vital in catching any potential issues early on and building confidence in the model's accuracy and robustness. In this series of tests, the airport indexed as 1 is the hub airport and airport 0 and 2 serve as the spokes.

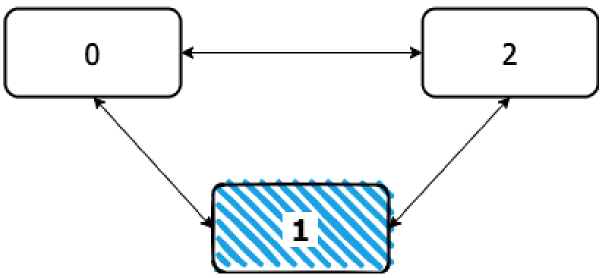

Figure 1.1: A simplified three-airport scenario for verification of the model where airport 1 is indexed as the hub

No Demand

In the absence of any passenger demand, no flights were scheduled between the airports. This result aligns with the model's objective to minimise costs, confirming that without revenue potential from passenger demand, operations remain inactive.

Only demand between airport 1 and airport 0

- **Low demand:** When demand between airport 1 and airport 0 was low, the revenue generated was insufficient to cover the operational costs of the flight. As a result, the model did not schedule any flights, demonstrating that the cost-benefit threshold for flight operation was not met.

- **High demand:** When the demand between airport 1 and airport 0 increased, the revenue surpassed the operating costs, prompting the model to schedule flights. This scenario highlights the model's sensitivity to demand levels and its ability to adjust operations when demand is high enough to justify the costs.

Only demand between airport 0 and airport 2

- **Low demand:** With low demand between airport 0 and airport 2, the model recognised that operating the route would not be profitable. Since flights only occur between the hub and the spokes, serving this demand would require flying an empty aircraft from airport 1 to airport 2 before picking up passengers for the return leg. The cost of this empty positioning flight, combined with the insufficient demand, made the operation not economically viable. Consequently, no flights were scheduled.

- **High demand:** When demand between airport 0 and airport 2 increased, the model determined that the revenue generated from this route could cover the costs, even considering the empty positioning flight from airport 1 to airport 2. In this case, an aircraft would fly empty from the hub (airport 1) to airport 2, pick up passengers, and then return to the hub before continuing to airport 0 or another destination. The model responded by scheduling flights on this route, indicating that at higher demand levels, it is economically feasible to serve this route despite the inefficiencies associated with the empty positioning leg.

Demand between airport 0 and airport 1, and airport 0 and airport 2

- **Low demand between airport 0 and airport 1 and low demand between airport 0 and airport 2:** In this scenario, with both demands being low, the model determined that operating flights was not cost-effective. Consequently, no flights were scheduled between any of the airports. This result confirms that insufficient demand does not justify the operational costs of flights, including the empty legs associated with flying between the hubs and spokes.

- **High demand between airport 0 and airport 1, and low demand between airport 0 and airport 2:** When demand was high between airport 0 and airport 1, but low between airport 0 and airport 2, the model scheduled flights between airport 0 and airport 1 only. Despite high demand between 0 and 1, the low demand between 0 and 2 did not justify the cost of flights involving empty legs. Thus, flights were scheduled to maximise revenue where demand was sufficient.

- **Low demand between airport 0, and airport 1 and high demand between airport 0 and airport 2:** With low demand between airport 0 and airport 1 and high demand between airport 0 and airport 2, the model scheduled flights between all relevant airports (0-1 and 1-2). Although demand between 0 and 1 was insufficient to cover operational costs on its own, the high demand between 0 and 2 made it economically viable to operate flights including the empty leg from 1 to 2.

- **High demand between airport 0 and airport 1, and high demand between airport 0 and airport 2:** When both demands were high, the model scheduled flights between airport 0 and airport 1, and between airport 1 and airport 2. The high demand levels justified the operational costs of all flights, including those with empty legs. This result highlights that when demand is sufficiently high across all routes, the model maximises connectivity by operating flights even with the additional cost of empty legs.

These test scenarios confirm that the model is functioning as expected, dynamically adjusting flight schedules based on the balance between demand and operational costs. The model successfully identifies when it is and isn't profitable to operate flights, considering demand levels and the additional cost burden of operating empty legs.

Table 1.1: Three-airport model response different demand scenarios

Scenario	Demand Level	Expected response	Passed
None	None	No flights	✓
0 - 1	Low	No flights	✓
	High	Flights (0-1)	✓
0 - 2	Low	No flights	✓
	High	Flights (0-1, 1-2)	✓
0 - 1, 0 - 2	Low (0-1), low (0-2)	No flights	✓
	High (0-1), low (0-2)	Flights (0-1)	✓
	Low (0-1), High (0-2)	Flights (0-1, 1-2)	✓
	High (0-1), High (0-2)	Flights (0-1, 1-2)	✓

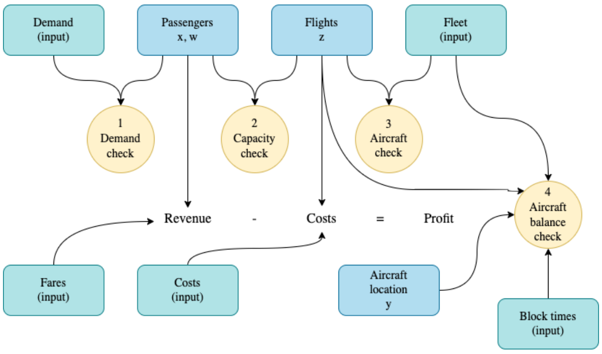

Figure 1.2: Verification plan for airline scheduling model

Full scale model tests

To systematically test the full scale model, a verification plan was made, which is visualised in figure 1.2. This shows that the model must adhere to the following conditions.

1. **Demand check:** Check if the passenger flows don't exceed the demand, i.e. confirm that there are no more passengers transported than willing to fly.
2. **Capacity check:** Check if the passenger flows do not exceed the available number of seats.
3. **Aircraft check:** Check if there aircraft available on the departure airports to facilitate the flights.
4. **Aircraft balance check:** Check if the incoming and departing aircraft at every airport balance out, i.e. are there no aircraft disappearing in the void?

These tests are done for the full scale model using Excel. An overview of all test and outcomes of the test can be found in table **??**.

Demand check

Two checks are done regarding the demand that goes into the model. The first check makes sure that there are no more passengers transported between every origin and destinations than the demand. The total number of passengers transported between every origin i and destination j is composed of the direct passengers $x_{ijt_ot_a}$ and $w_{ijt_ot_at_2}$, which cannot be higher than the the total demand for that OD-pair. The second check verifies that the passengers do not travel more than two hours earlier or two hours later than their original desired departure time.

Capacity check

The total number of passengers from every origin i to every destination j with actual departure time t_a should not be higher than the total number of seats available on departing aircraft in that time slot, taking the load factor of 0.9 into account. The passengers on every flight consist of direct passengers, transfer passengers that are on the first leg of their journey and transfer passengers that are on the second leg of their journey.

Aircraft checks

To ensure that the number of aircraft remains consistent throughout the model's timeline, a comprehensive aircraft number completeness check was conducted. This involved verifying that the number of aircraft at each time period matched the expected total number of aircraft.

To determine the total aircraft count per time period t, the sum of the aircraft located at the airports was calculated, as represented by decision variable y_{ikt}, along with the number of aircraft currently in flight. The variable y_{ikt} provides the location of each aircraft at a given time period, which was used to calculate the number of aircraft on the ground at various airports during that time period. Decision variable $zijkt$ represents departing flights at time t. To determine how many aircraft were in flight during each time period, the block time BT of each flight was used. From this, the arrival time slot of the flight was derived. For each time period, it was checked how many aircraft of type k were in the air. An aircraft was considered to be in the air if there was a flight assigned to that aircraft type during the given time period t, i.e., departure time $< t \leq$ arrival time.

To validate the overall aircraft count, an aircraft tracker was employed. For each time period, the number of aircraft on the ground at the airports and the number of aircraft in transit were summed. This sum was compared to the total number of aircraft of that type, ensuring consistency across all time periods. This aircraft number completeness check is crucial for ensuring that no aircraft are lost or double-counted in the model, thus providing confidence that the model accurately tracks all aircraft throughout its operation.

Validation of the model

Validation, on the other hand, is about ensuring that the model accurately reflects reality. It checks if the right model was built by comparing the model's outcomes with real-world data or expert expectations. This step is particularly important in making sure that the model is not only correct on paper but also relevant and applicable in practice.

Passengers

In 2022 KLM reports to have transferred almost 26 million passengers, with a daily average of 71 thousand transferred passengers [28]. In the baseline run with a current fleet, a total number of 87,702 passengers is reached, proving that the model in this research simulates a network that is comparable to the current situation at KLM.

Connectivity model

The Airports Council International Europe (ACI EUROPE) states in their connectivity report that Schiphol airport had a Netscan connectivity score of 41,659 for June 2024 [4]. When dividing that by 30 in order to find the daily connectivity in that month, a score of 1,389 is found. As can be seen in table **??** the baseline Netscan connectivity of the model in this research lies around 1,300, proving that thee connectivity scores generated are comparable to the scores of existing networks.

2
Model analysis

In figure 2.1 it is evident that the morning hours are the most profitable period for flights. As the day progresses, load factors decline, and profitability diminishes, with certain flights even incurring losses. This pattern can be largely attributed to the study's requirement that all aircraft return to the hub by the end of the day. This operational constraint forces the airline to schedule return flights, even during periods of low demand, which results in flights operating with under-filled cabins. Consequently, the revenue generated by these flights is often insufficient to cover the associated costs, leading to decreased profitability or even financial losses during these times of the day. This highlights the significant impact that hub-based scheduling can have on an airline's overall profit margins, particularly when operational flexibility is limited by such constraints.

Figure 2.2 and figure 2.3 the daily utilisation of aircraft in the old fleet, specifically types 0, 2, and 4, is visualised. The patterns in the first two figures reveal a clear wave-like motion throughout the day. At the beginning of the day, all aircraft are positioned at the hub, which aligns with the study's requirement for all planes to return to the hub by the end of each day. By mid-morning, the short-haul flights reach their destinations, leaving a substantial number of aircraft grounded. These aircraft are then ready for their next departures, leading to a gradual return to the hub around midday. During this time, the longer-haul flights also arrive at their destinations, contributing to a peak in the number of parked aircraft. This cyclical wave pattern repeats in the latter half of the day, culminating with all aircraft back at the hub by day's end.

In contrast, Figure 2.4, which illustrates the behaviour of aircraft type 4, shows a different pattern. The wave-like motion is far less pronounced. This is in line with expectations, as type 4 aircraft, being the smallest in the fleet, are predominantly used for short-haul flights and can be more evenly deployed throughout the day. This allows for more consistent utilisation, reducing the large fluctuations in aircraft positioning seen with the larger aircraft types, which are more bound by the constraints of longer block times.

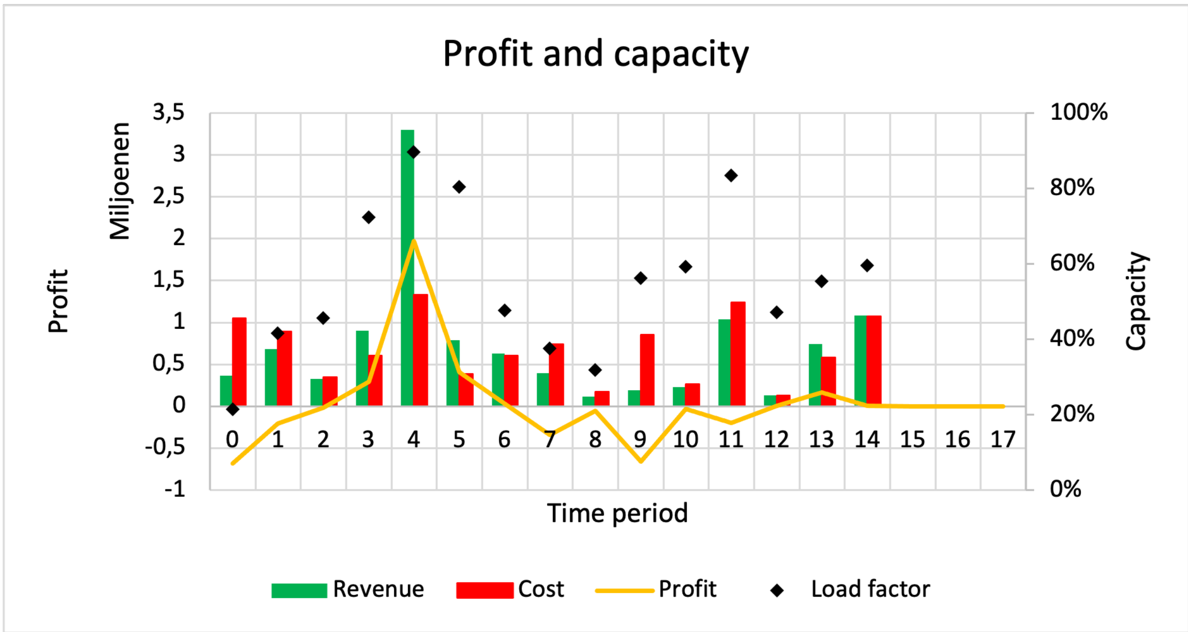

Figure 2.1: Caption

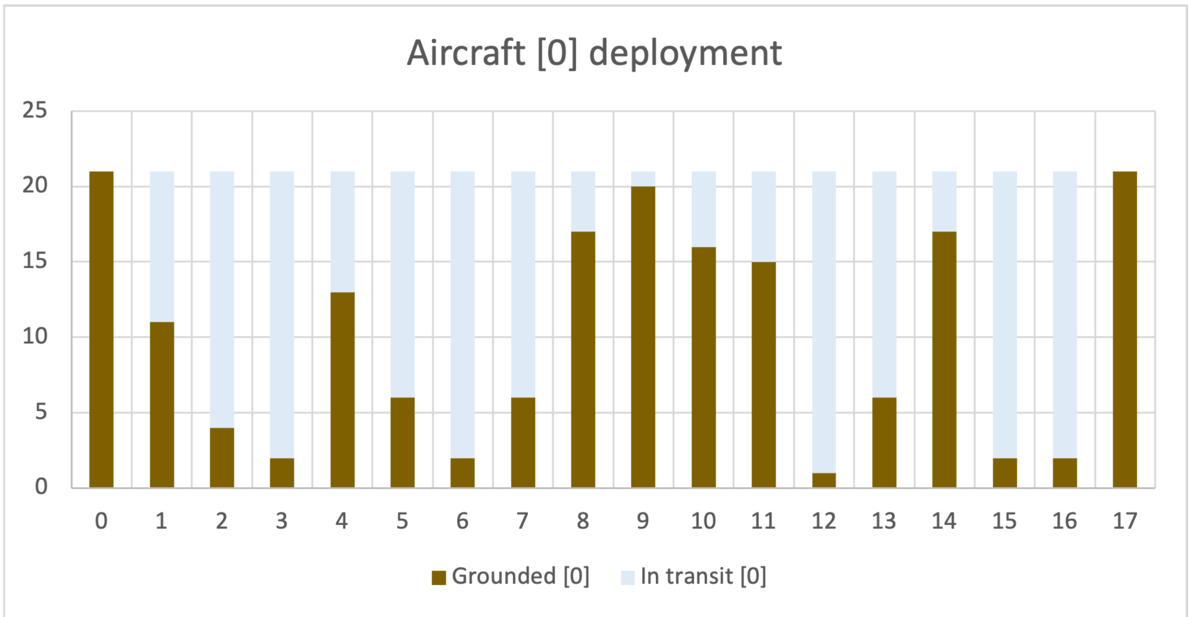

Figure 2.2: Use of aircraft type 0 in scenario 1

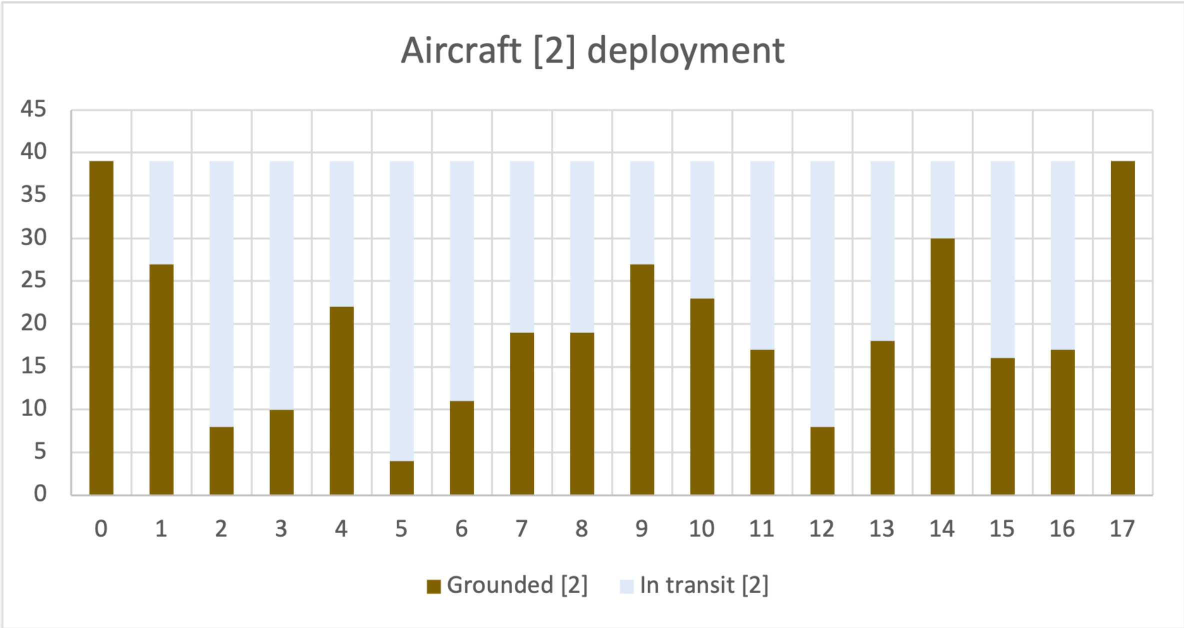

Figure 2.3: Use of aircraft type 2 in scenario 1

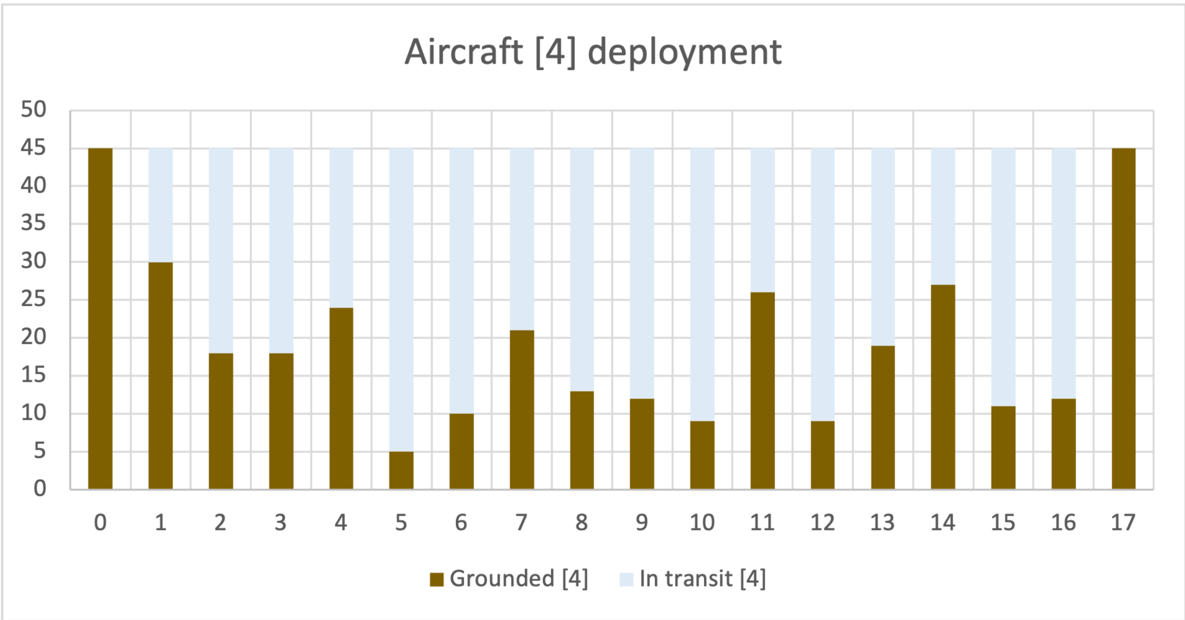

Figure 2.4: Use of aircraft type 4 in scenario 1

Bibliography

[1] A. Budde1, G. Burghouwt, J. de Wit. Borrowing from Behavioural Science: A Novel Method for the Analysis of Indirect Temporal Connectivity at Airport Hubs. Proceedings of the 12th Air Transport Research Society (ATRS) World Conference, 2008.

[2] A. Danesi. Measuring airline hub timetable co-ordination and connectivity: definition of a new index and application to a sample of European hubs. European Transport, 34:54–74, 2006.

[3] ACI EUROPE. Airport Industry Connectivity Report. 2022.

[4] ACI EUROPE. Airport Industry Connectivity Report. 2024.

[5] Alexander Koch, Björn Nagel, Volker Gollnick, Katrin Dahlmann, Volker Grewe, Bernd Kärcher, Ulrich Schumann. Integrated analysis and design environment for a climate compatible air transport system. 9th AIAA Aviation Technology, Integration and Operations Conference, 2009.

[6] Andrea Gualini, Li Zou, Martin Dresner. Airline strategies during the pandemic: What worked? Transportation Research Part A: Policy and Practice, 170, 2023.

[7] Becky P.Y. Loo, Linna Li, Voula Psaraki, Ioanna Pagoni. CO2 emissions associated with hubbing activities in air transport: an international comparison. Journal of Transport Geography, 34:185–193, 2014.

[8] J. Benjamin. Ministerie: krimp is de enige optie om geluidsoverlast schiphol te beperken. NRC. URL https://www.nrc.nl/nieuws/2022/11/15/ministerie-krimp-is-de-enige-optie-om-geluidsoverlast-schiphol-te-beperken-a4148348.

[9] Bo Zou, Gurkaran Singh Buxi, Mark Hansen. Optimal 4-D Aircraft Trajectories in a Contrail-sensitive Environment. Networks and Spatial Economics, 16:415–446, 2013.

[10] Brandon Graver, Ph.D., Kevin Zhang, Dan Rutherford, Ph.D. CO2 emissions from commercial aviation, 2018. The International Council on Clean Transportation, 2019.

[11] Bruno Santos. AE4423 Airline Planning and Optimization 2018/2019 Q2, lecture 1.

[12] B.S. Levine, H.O. Gao. Aircraft Taxi-Out Emissions at Congested Hub Airports and Implications for Aviation Emissions Reduction in the United States. Transportation Research Board, 86th Annual Meeting, 2007.

[13] David S.Lee, David W.Fahey, Piers M.Forster, Peter J.Newtond, Ron C.N.Wite, Ling L.Lim, Bethan Owen, Robert Sausen. Aviation and global climate change in the 21st century. Atmospheric Environment, 43 (22-23):3520–3537, 2009.

[14] Dr Christian N. Jardine. Calculating the Environmental Impact of Aviation Emissions. Climate Care - University of Oxford, 2005.

[15] Dragana Vujovíc, Nedeljko Torodovíc. An assessment of pollutant emissions due to air traffic at NikolaTesla International Airport, Belgrade, and the link between local airquality and weather types. Transportation Research Part B, 56:85–94, 2017.

[16] D.S. Katz, L.A. Garrow. Revenue and operational impacts of depeaking at U.S. hub airports. Journal of Air Transport Management, 34:57–64, 2014.

[17] G. Burghouwt. Influencing Air Connectivity Outcomes. Prepared for the Roundtable on Capacity building through efficient use of existing airport infrastructure, 9-10 March 2017, Querétaro, (Discussion Paper No. 2017-24).

[18] G. Burghouwt, J. de Wit. Temporal configurations of European airline networks. Journal of Air Transport Management, 11(3):185–198, 2005.

[19] G. Burghouwt, R. Redondi. Connectivity in Air Transport Networks, An Assessment of Models and Applications. Journal of Transport Economics and Policy, 47:35–53, 2013.

[20] Germà Bel, Xavier Fageda. Getting there fast: globalization, intercontinental flights and location of headquarters. Journal of Economic Geography, 8(4):471–495, 2008.

[21] Royal Schiphol Group. CO_2 Neutral Airport, 2023. URL https://www.schiphol.nl/en/schiphol-group/page/a-co2-neutral-airport/. 23-03-2023.

[22] IATA. Air Connectivity: Measuring the connections that drive economic growth. 2020.

[23] J. Veldhuis. The competitive position of airline networks. Journal of Air Transport Management, 3(4): 181–188, 1997.

[24] Jaap Bouwer, Alex Dichter, Vik Krishnan, Steve Saxon. The six secrets of profitable airlines. McKinsey & Company, 2022.

[25] Jasper Faber, Stefan Grebe, Daan Juijn, Julius Király, Louis Leestemaker, Christiaan Meijer (CE Delft), Peter Frankena, Jerry Knuyt (ADECS Airinfra), Evert Windels (ADSE), Floris de Haan (Erasmus University Rottredam), Gijs van Eck, Marco Kouwenhoven (Significance), Andre van Velsen (TAKS). Impacts of a CO2 ceiling for Dutch aviation. CE Delft for Ministry of Infrastructure and Water Management, October 2022.

[26] Jim Hamill. Competitive strategies in the world airline industry. European Management Journal, 11(3): 332–341, 1993.

[27] J.K. Brueckner, M.H. Lin. Convenient flight connections vs. airport congestion: Modeling the 'rolling hub'. International Journal of Industrial Organization, 48:118–142, 2016.

[28] KLM Royal Dutch Airlines. Annual Report 2022 - New Perspectives. 2023.

[29] Lynnette Dray, Antony Evans, Tom Reynolds, Andreas W. Schäfer, María Vera-Morales, Wolfram Bosbach. Airline fleet replacement funded by a carbon tax: An integrated assessment. Transport Policy, 34(75-84), 2014.

[30] M. Givoni, P. Rietveld. The environmental implications of airlines' choice of aircraft size. Journal of Air Transport Management, 16:159–167, 2010.

[31] Maria Nadia Postorino, Luca Mantecchini. A transport carbon footprint methodology to assess airport carbon emissions. Journal of Air Transport Management, 37:76–86, 2014.

[32] Maria Nadia Postorino, Luca Mantecchini. Connectivity carbon and noise levels in the airport neighbourhood. Transport Policy, 79:204–212, 2019.

[33] Mariasole Banno and Renato Redondi. ir Connectivity and Foreign Direct Investments: Economic Effects of the Introduction of New Routes. European Transport Review, 6(4):355–363, 2014.

[34] Mattia Grampella, Gianmaria Martini, Davide Scotti, Giovanni Zambon. The factors affecting pollution and noise environmental costs of the current aircraft fleet: An econometric analysis. Transportation Research Part A: Policy and Practice, 92:310–325, 2016.

[35] Michael Hepting, Henry Pak, Wolfgang Grimme, Katrin Dahlmann, Martin Jung, Dieter Wilken. Climate impact of German air traffic: A scenario approach. Transportation Research Part D: Transport and Environment, 85, 2020.

[36] Michael Rosskopf, Stephan Lehner, Volker Gollnick. Economic–environmental trade-offs in long-term airline fleet planning. Journal of Air Transport Management, 34:109–115, 2014.

[37] A. Nandram. Minister: krimp schiphol is tijdelijk, vanaf 2027 ongelimiteerd vliegen met 'schone' vliegtuigen. de Volkskrant. URL https://www.volkskrant.nl/nieuws-achtergrond/minister-krimp-schiphol-is-tijdelijk-vanaf-2027-ongelimiteerd-vliegen-met-schone-vliegtuigen

[38] Nienke Zoetbrood. Dankzij schonere vliegtuigen mag Schiphol straks toch weer groeien. Hoe staat het ervoor met die toestellen? de Volkskrant, 18-01-2023.

[39] N.K. Taneja, G. Burghouwt. Transforming airlines. Routledge, 2020.

[40] N.P. Dennis. Scheduling strategies for airline hub operations. Journal of Air Transport Management, 1 (2):131–144, 1994.

[41] N.P. Dennis. Airline hub operations in Europe. Journal of Transport Geography, 2(4):219–233, 1994.

[42] Council of the EU and the European Council. European Green Deal, 2022. URL https://www.consilium.europa.eu/en/policies/green-deal/. 29-03-2023.

[43] Council of the EU and the European Council. Fit for 55, 2023. URL https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/. 29-03-2023.

[44] P. Malighetti, S. Paleari, R. Redondi. Connectivity of the European airport network: "Self- help hubbing" and business implications. Journal of Air Transport Management, 14(2):53–65, 2008.

[45] P.D. Bootsma. Airline flight schedule development; analysis and design tools for European hinter- land hubs. PhD Thesis, University of Twente, Utrecht, 1997.

[46] Peter Belobaba, Amedeo Odoni and Cynthia Barnhart. The Global Airline Industry. John Wiley and Sons, Ltd., 2009.

[47] Peter Morrell, Cherie Lu. The environmental cost implication of hub–hub versus hub by-pass flight networks. Transportation Research Part D: Transport and Environment, 12, 2007.

[48] R. Doganis, N.P. Dennis. Lessons in Hubbing. Airline Business, pages 42–47, 1989.

[49] Ravishankara, A.R. Nitrous Oxide: A Greenhouse Gast That is Also an Ozone Layer Depleting Gas. American Geophysical Union, 2015.

[50] Renato Redondi, Paolo Malighetti, Stefano Paleari. De-hubbing of airports and their recovery patterns. Journal of Air Transport Management, 18(1):1–4, 2012.

[51] Rijksoverheid - Ministerie van Infrastructuur en Waterstaat. Verantwoord vliegen naar 2050, Luchtvaartnota 2020-2050. 2020.

[52] S. Paleari, R. Redondi, P. Malighetti. A comparative study of airport connectivity in China, Europe and US: which network provides the best service to passengers? Transportation Research Part E: Logistics and Transportation Review, 46(2):198–214, 2008.

[53] Schiphol. Schiphol traffic review 2021. URL https://www.schiphol.nl/en/schiphol-group/page/traffic-review/.

[54] Schiphol. Schiphol and the future - Staying in balance with the local area, 2013. URL https://www.schiphol.nl/en/schiphol-as-a-neighbour/page/schiphol-and-the-future/. 10-03-2023.

[55] Selcuk Ekici, Murat Ayar, Ugur Kilic, T. Hikmet Karakoc. Performance based analysis for the Ankara-London route in terms of emissions and fuel consumption of different combinations of aircraft/engine: An IMPACT application. Journal of Air Transport Management, 108, 2023.

[56] S.L. Shaw, R.J. Ivy. Airline mergers and their effect on network structure. Journal of Transport Geography, 2(4):234–246, 1994.

[57] Stefan Grebe, Christiaan Meijer, Julius Király, Louis Leestemaker. Updated impacts of a CO2 ceiling for Dutch aviation. CE Delft for Ministry of Infrastructure and Water Management, December 2022.

[58] Stelios Pesmajoglou. Carbon Offsetting and Reduction Scheme for International Aviation - CORSIA. ICAO capacity building seminar on low emissions aviation measure, 2018.

[59] Sun, Junzi and Hoekstra, Jacco M and Ellerbroek, Joost. OpenAP: An open-source aircraft performance model for air transportation studies and simulations. Aerospace, 7(8):104, 2020.

[60] Thirupathi Boningari, Panagiotis mirniotis. Impact of nitrogen oxides on the environment and human health: Mn-based materials for the NO_x abatement. Current Opinion in Chemical Engineering, 13:133–141, 2016.

[61] Tommy K.Y. Cheung, Collin W.H. Wong, Anming Zhang. The evolution of aviation network: Global airport connectivity index 2006–2016. Transportation Research Part E: Logistics and Transportation Review, 133, 2020.

[62] United States Environmental Protection Agency. Health and Environmental Effects of Particulate Matter (PM). 2013.