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Airline Collaborative Network Planning to mitigate Environmental Impact

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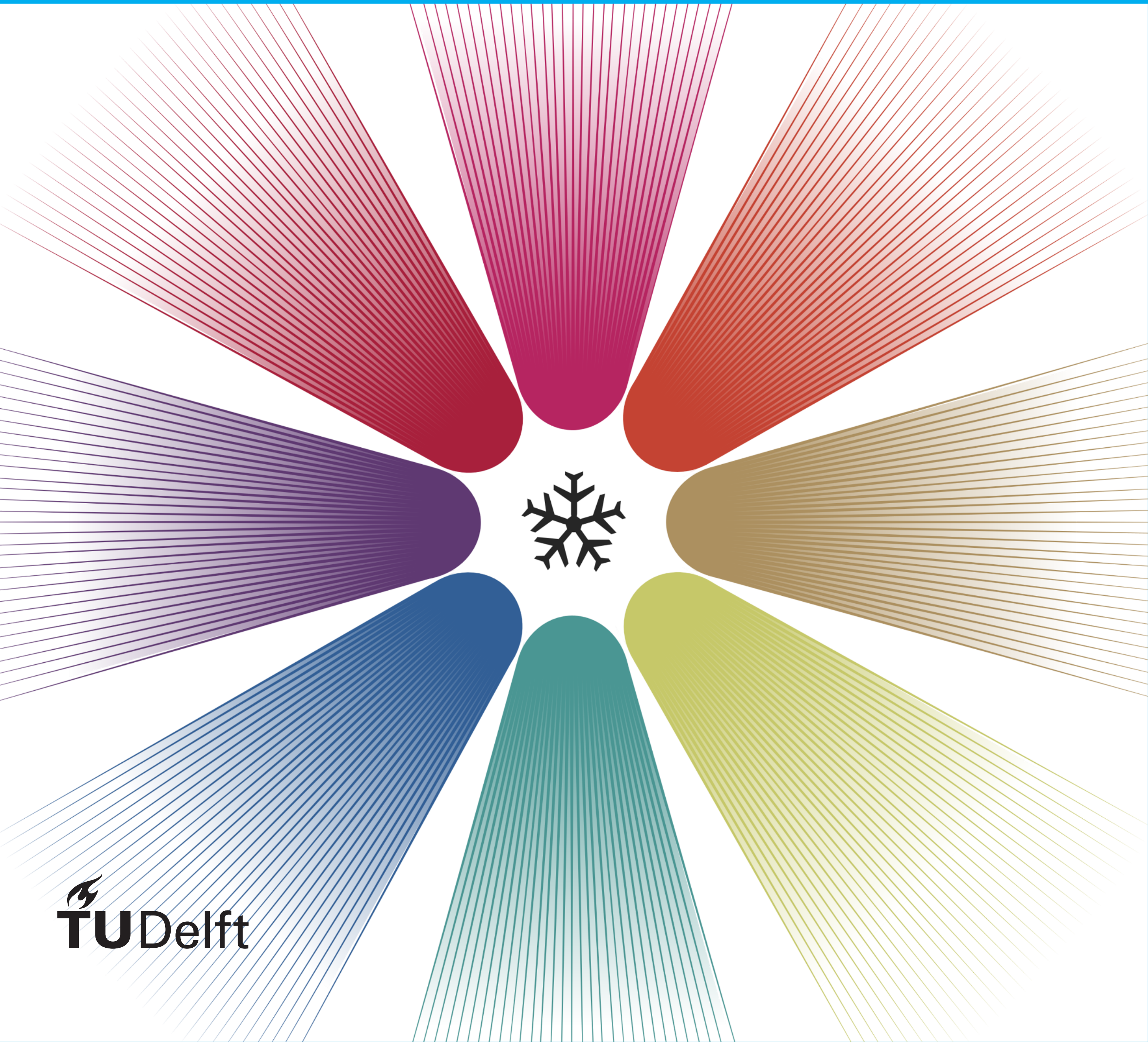

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by

Edoardo Verzotti

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Edoardo Verzotti
Delft, November 2023

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List of Abbreviations

CO_2	Carbon dioxide
NO_x	Oxides of Nitrogen
SO_x	Sulphur Oxides
aCCF	Algorithmic Climate Change Functions
ADS-B	Automatic Dependent Surveillance-Broadcast
ATR	Average Temperature Rise
B&B	Branch and Bound algorithms
CCF	Climate Change Functions
CNP	Contract Net Protocol
ETP	Environmental Taxation Parameter
ETS	European Trading Scheme
EU	European Union
FA	Full Alliance
FAM	Fleet Assignment Model
GDP	Gross Domestic Product
GHG	Green House Gas
GT	Game Theory
GTP	Global Temperature Change Potential
GWP	Global Warming Potential
H&S	Hub Spokes
IFAM	Itinerary-based Fleet Assignment Model
ILP	Integer Linear Programming
IPCC	Intergovernmental Panel on Climate Change
JV	Joint Venture
KL	KLM Royal Dutch Airlines (Koninklijke Luchtvaart Maatschappij)
KPI	Key Performance Indicator
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MSE	Mean Square Error
RF	Radiative Forcing

SC	Sharing Coefficient
TAT	Turn-Around Time
TP	TAP Air Portugal
TSN	Time-Space Network

Introduction

The founding concept of this thesis sprouted from an informal discussion with Dr.Gemke, Director Governance, Alliances, Sustainability, CIO-Office at Air France-KLM, over the possibility to incorporate collaboration between airlines to reduce the overall impact on the environment. A new methodology has been developed to add new collaboration opportunities in a network and frequency planning optimisation model. The initial model, which is then expanded and modified in this project, allows airlines to strategically plan their long term operations encompassing destinations and flight frequencies. It was presented during the Master of Science by Prof. Santos. The competences related to the environmental impact generated by airborne emissions were also provided in the Master of Science of Sustainable Air Transport. The theoretical background for this section of the project was provided Prof. Dedoussi. The knowledge obtained during the courses was re-elaborated by the student in an independent way to introduce proper modifications with the goal of adapting them to the necessities of the working world. The main goal of the project is to assess the potential benefits obtained by additional collaboration stages in the strategical planning of the airlines. The analysis aims at evaluating if a collaboration strategy based on sharing passenger demand could prove to be effective to reduce the impact of emissions without sacrificing the profitability of the airlines involved. If such expectations are achieved, it could point at the possibility of obtaining actual benefits through the implementation of this approach by the airlines.

Overall, this thesis projects looks to the future with hope, aiming at a future scenario where the services provided by the airlines could align with the crucial goals of reducing the anthropogenic footprint on the environment. This thesis report is organised as follows: In Part I, the Scientific Paper is presented; this chapter of the work includes the key aspects of the thesis encompassing the Methodology, a Case Study and the relative analysis of the conclusive results. Part II contains the relevant Literature Study that supports the research. Finally, in Part III, some additional results generated during the case study are presented.

I

Scientific Paper

Airline Collaborative Network Planning to mitigate Environmental Impact

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Abstract

In recent years, the aviation industry has faced escalating environmental scrutiny, prompted by the global shift towards heightened environmental awareness. This study explores a collaboration framework set up by airlines that envision to partially or totally shoulder the environmental impact costs generated by their airborne emissions. The methodology developed includes the production of detailed emissions data to be employed during the airlines planning strategy. The model conceived introduces a taxation approach exploited by airlines to include and incentive more environmentally sustainable solutions and a collaboration mechanism based on the possibility of sharing passenger demand between collaborating airlines. The environmental incentive and collaboration are implemented in a Linear Programming Network and Frequency Planning model with the goal of maximising airline profitability. A case study is analysed, focusing on two airlines, KLM and TAP, collaborating to achieve improved environmental and economic performance. The airlines engage in a scenario where the environmental impact externalities generated by airborne operations are shouldered by the airlines themselves. Employing the model developed, the airlines explore solutions that either reduce the environmental impact or solely maximise the profit of the two airlines. The results underscore the potential benefits of including collaboration in the airlines planning strategy, with a total 1.33% reduction in environmental impact when prioritising environmental cost abatement. Collaboration also demonstrated to be a consistent tool to achieve a profit recovery, showing up to a total anticipated profit increase of 2.21% when prioritising profitability or 0.71% when the priority is given to environmental impact reduction. In conclusion, this study highlights the potential efficacy of collaboration in addressing aviations environmental and economic challenges.

1 Introduction

In recent years, a global transformation in our perspective on the environment has emerged, gaining unprecedented prominence across industries. The urgency of near-term integrated climate action, as emphasised in the 2023 IPCC report [Calvin et al. (2023)], underscores the importance that climate change has both on human well-being and planetary health. The shift to this growing significance of environmental concerns in contemporary times is particularly pronounced in the transportation field, and specifically for the aviation sector.

The escalating environmental emphasis within aviation prompts a crucial question: How can airlines chart a course towards higher environmental efficiency while preserving their competitive edge? The answer may lie in innovative collaborations aimed at identifying more effective operational solutions. This research project analyses environmental externalities within the aviation sector and delves into the potential of collaborative strategies in an attempt to assess the potential of these strategies in enabling airlines to attain greater environmental sustainability while maintaining their competitive advantage.

The model proposed in this paper introduces a collaborative strategy into airlines' network and frequency planning, while concurrently incentivizing a reduction in the environmental impact of their operations through a taxation-like system. Environmental taxation, including levies on transportation emissions, has assumed a consistent and significant role in the European Union's fiscal framework, accounting for approximately 6% of total taxation and 2.5% of GDP in recent years [Delgado et al. (2022)]. This underscores the prevalence and significance of taxation measures aimed at addressing environmental concerns within the EU. In the realm of aviation, the introduction of CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) [Secretariat (2018)] serves as a global market-based measure designed to replace the fragmented landscape of national or regional regulatory initiatives in addressing international aviation emissions.

The model presented in this paper envisions airlines operating on a Hub and Spokes network taking a virtuous initiative to shoulder, in the form of a taxation scheme, the environmental impact costs of their airborne operations, either partially or in their entirety. This taxation-like mechanism not only fosters environmental responsibility but also enhances collaboration between industry peers. The paper conceives of a cooperative

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framework designed to explore both improved environmental solutions and strategies to alleviate the financial pressure created by these additional environmental costs.

To guide planning strategies towards enhanced environmental outcomes, the model incorporates an evaluation of the emissions generated, on average, by each individual flight, aligning with the regulatory objectives outlined in the CORSIA agreement. This evaluation relies on access to detailed data concerning fleet and engine specifications. The emitted quantities then serve as the foundation for the conversion into monetary costs. The conversion facilitates the assessment of the impact of different chemical species generated and provides a quantifiable metric for airlines. The quantification of both climate and air quality impacts for each flight outlines the groundwork for the collaboration framework presented in this paper.

Various aspects of airline structures and operations can be considered when seeking novel avenues for profitability and reduced environmental impact through collaboration with industry peers. The model proposed focuses on the potential outcomes of two airlines engaging in a collaborative network and frequency planning initiative implemented through a profit maximisation linear programming objective. The collaboration is implemented in the airlines' network optimisation through the possibility of sharing part of the airlines' passenger demand. This cooperative strategy is inspired by code-share, while distinguishing itself from standard code-share in its time horizon, being part of the strategical planning of the airlines up to 1812 months prior to the day of operation, and its scope, prioritising shared routes instead of increasing the connectivity of the service offered through complementary networks. An example of the type of challenge tackled in this paper can be witnessed in the following chapter.

The hypothesis encompasses that, through the methodology, it will be possible to obtain enhanced profitability on both a collective and individual airline basis. Consequently, this research seeks to uncover the extent to which these collaborative initiatives may generate additional profits while simultaneously reducing the overall environmental footprint of airlines.

As the model evaluates the potential for improved environmental solutions, it also considers different approaches to the cooperative framework. The model will assess two different strategies: both applied to a collaboration implemented on a route basis; the first one prioritises the minimisation of environmental impact, while the second one reserves priority for the profitability of the airlines. With a more precise assessment of the effects of each flight, airlines can make informed decisions on how to strategically structure their operations and potentially reach a more effective solution, aligning with environmentally conscious practices.

2 Mock-up case

A mock-up of the model presented in this project can be seen in the following example. Given an Origin "O" and a Destination "D", two airlines, a_1 and a_2, want to transport passengers from O to D with connecting flights through their respective hub airports, namely H_1 and H_2 (Figure 1). Some illustrative input data for this mock-up can be seen in Tables 1.

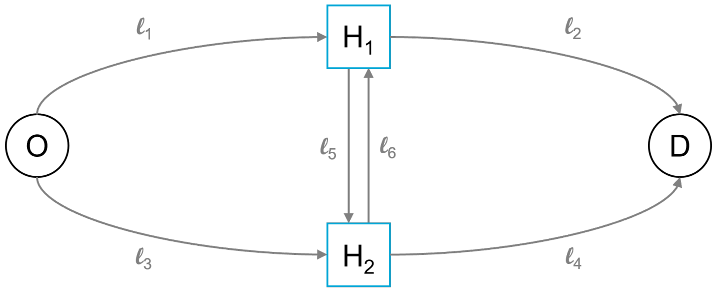

Figure 1: Mock-up case of the challenge tacked in this project.

Notation	*Airport*
H_1	AMS
H_2	LIS
O	FCO
D	JFK

Table 1: Mock-up case: airports considered.

The data shown in Tables 2 and 3 are indicative, yet they align with the data later employed in the case study considered. The fare, f_{ij}, and the airline's a weekly passenger demand, q_a, for each itinerary considered, going from origin i to destination j, in the mock-up are given in Table 3. In Table 2, the input data regarding the seat capacity of every aircraft type available is presented. In the same table, the operative costs, c_{OP}, and the environmental costs, c_{ENV}, are provided for each flight considered, as referenced in Figure 1. Only the flight and aircraft types relevant for this mock-up are presented.

Possible solutions, with and without the possibility to share passenger demand, are shown in Table 4. These results are obtained by simplifying the limitations imposed: no restriction is given on the number of aircraft to be used, no aircraft continuity is considered, and most significantly, an extremely limited portion of the network is considered. Despite these limitations, the solution to this mock-up case is not trivial and would require further optimisation.

Flight Leg	Aircraft	Seats	Op.Cost €	Env. Cost €
l_1	AC_1	180	8737	2259
	AC_2	100	7245	1769
l_2	AC_3	408	53043	35123
	AC_4	275	41646	18956
l_3	AC_5	216	14416	4629
	AC_6	110	9641	2313
l_4	AC_7	269	38867	21841
	AC_8	298	41215	26194
l_5	AC_1	180	11115	2897
	AC_2	100	9217	2321
	AC_5	216	14459	4644
	AC_6	110	9669	2321
l_6	AC_1	180	11115	2885
	AC_2	100	9217	2313
	$AC5$	216	14459	4626
	AC_6	110	9669	2313

Table 2: Seat and flight costs for mock-up case.

Itinerary ij	f_{ij} €	q_{a_1}	q_{a_2}
OH_1	187	3492	0
OH_2	260	0	2401
H_1H_2	208	1970	1287
H_2H_1	208	1567	2041
H_1D	900	3213	17
H_2D	914	0	585
OD	910	33	141

Table 3: Fare and weekly passenger demand for mock-up case.

In Table 5, it is possible to witness how the solutions are achieved. The difference between the two analyses was obtained by sharing 18 passengers travelling on OD, 8 on H_1H_2, and 233 on H_2H_1 from the second airline to the first. This collaboration mock-up achieves an improvement in both profitability and environmental impact. However, considering the complexity of the full-scale model and the simplification made for this mock-up, no conclusion can be extrapolated from this introductory analysis alone.

Scenario	Profit [k€]	Op.Cost [k€]	Env.Cost [k€]
No Collab.	4954	1351	579.2
Collab	4971	1334	575.1
Δ Collab	17.28	-17.28	-4.061
Collab.rel.	0.3%	-1.3%	-0.7%

Table 4: Mock-up case results.

Flight Leg	Aircraft Used (No Collab.)	Aircraft Used (Collab.)
l_1	20 AC_1	20 AC_1
l_2	8 AC_3	8 AC_3
l_3	12 AC_5	12 AC_5
l_4	3 AC_7	3 AC_7
l_5	11 AC_1, 6 $AC5$, 1 AC_6	11 AC_1, 6 AC_5
l_6	9 AC_1, 9 AC_5, 1 AC_6	10 AC_1, 8 AC_5, 1 AC_6

Table 5: Aircraft used for solving the mock-up case.

3 Literature Review

This chapter presents relevant findings in the literature, focusing on the two core aspects analysed by the model proposed in this document, these being the environmental impact and the airline planning process.

Environmental Impact

The aviation industry's environmental impact has gained significant attention in recent decades due to global environmental concerns. This section presents a review of the literature in this field from the past decade using the following keywords: "Airline", "Environment","Environmental Impact", "Emission", "Air quality", "Non-CO_2 effects", and "Climate sensitivity". Backward and forward snowball methods were also applied. Three prominent research groups leading in this field are the Deutsches Zentrum für Luft- und Raumfahrt, Technische Universitat Dresden (Germany), and Delft University of Technology (The Netherlands).

To quantify the environmental impact, it is crucial to select an appropriate climate metric. No consensus exists on the optimal metric due to its specificity. Some metrics are based on simplifications and approximations, making the choice complex. Scheelhaase et al. (2016) underlined the importance of properly choosing a metric over another while stating that no broad consensus has yet been reached among the scientific community as to which is the optimal metric. One of the earliest approaches was to use emissions as a climate metric. Grewe and Dahlmann (2015) underlines that such a metric does not provide any information on climate impacts. To convert such metric to precisely weighted climate impact, it is possible to use the conversion parameters provided in Grobler et al. (2019), encompassing both climate and air quality effects and translating these impacts into economic costs. Examples of its applicability can be found in flight trajectory optimisation strategies and policymaking [Lindner et al. (2016) and Niklaß et al. (2021)].

Two main strategies have been identified to impose environmental protection measures on the industry. A "command-and-control" approach sets thresholds and applies penalties for emissions exceeding limits [Tone (2019)], and "trading schemes" trade emissions allowances for aviation's climate-relevant species and convert them into monetary values [Scheelhaase et al. (2016)]. The European Union's European Trading Scheme (ETS) is an example. This taxation-like approach allows for the inclusion of the effects of various chemical species in airlines' operational costs.

Various tools have been used to simulate aviation's emissions. TOMATO is a modular simulation environment for trajectory optimisation and air traffic management assessment [Rosenow and Fricke (2019)]. Examples of its usage can be found in Lindner et al. (2016), Förster et al. (2016), Rosenow et al. (2017), Rosenow and Fricke (2017), Lindner et al. (2018), Rosenow and Schultz (2018), and Rosenow and Fricke (2019). TOM focuses on climate-optimised aircraft trajectories [Niklaß et al. (2018)]. OpenAVEM adopts a bottom-up approach to evaluate emissions for individual flights [Quadros et al. (2022)]. OpenAVEM offers adaptability and accessibility, which well suit the specific needs of this research.

Airline Planning

The identification of different phases in the decision-making process of airline planning has evolved over time. Initially, these phases encompassed network definition, schedule planning, fleet planning, dispatching, and routing, as outlined by Simpson (1969). Over time, refinements led to the categorisation of tasks into schedule design, fleet planning, aircraft maintenance routing, and crew scheduling, as presented by Barnhart and Cohn (2002). Additionally, Deveci and Demirel (2015) emphasised the increasing significance of maintenance and crew considerations. In contemporary literature, like Wen et al. (2021), the airline planning process is divided into three major sections: Strategy Planning, Tactical Planning, and Operation Planning, each involving various sub-tasks. These phases and tasks are theoretical distinctions that may overlap in practice. Within Strategic Planning, which occurs well in advance of the operational phase, elements such as market analysis and hub location significantly influence the type of service an airline will offer. While airlines may not always have full control over these strategic choices due to various internal and external factors, they tend to adopt either a Point-to-Point or Hub-and-Spoke architecture [Cook and Billig (2017)]. Various studies, including Alderighi et al. (2007), have proposed methods to determine how closely airlines align with these architectural choices. Network and Frequency Planning within Strategic Planning are crucial for resource allocation and long-term operational impacts, involving decisions about which connections to cover and recommended frequencies. This phase heavily relies on demand forecast data, with challenges related to dynamic demand. Gravity models, as explored by Birolini et al. (2020), are used to forecast demand, assuming independent origin and destination pairs.

Airlines may collaborate in various ways and layers. Cooperation agreements in the aviation sector are categorised, according to Fageda et al. (2019), into Full Alliance (FA), Joint Venture (JV), and Merger. These agreements can involve revenue sharing, mainly for FA, cost sharing, mainly for JV, and deeper antitrust immunity. An analysis of the effects of these strategies applied fairly to different players can be found in Yea et al. (2018) and Yea et al. (2022). These two papers emphasise equitable distribution and cooperative efforts among airline alliances to secure profits through sustainable collaboration, acknowledging the need to consider specific alliance types and competition dynamics while advocating for a mutually beneficial approach that supports global sustainability and societal development.

The interaction in a collaborative agreement relies on the information exchange between the participants. It must, however, not be overlooked the importance of sharing data in a competitive sector such as the aviation industry. Olgun (2022) identifies and labels three main ways in which information can be shared, ranging from fully disclosed (White) to partially (Grey) or minimally (Black). Incomplete information sharing can lead to more complex modelling and suboptimal results [Wright (2014)].

A widely employed approach to implementing collaboration between airlines is code-sharing. Code-share can be identified as a revenue-sharing strategy, common in the FA agreement. It involves marketing seats on a flight operated by another carrier [Fageda et al. (2019)]. Code-share agreements comprise over 6% of major airlines' revenues [Gerlach et al. (2013)]. Research by Zou and Chen (2017) shows a positive correlation between code-sharing partners and airline operating margins. However, code-share carries risks, impacted by revenue management and pricing. As described in Gerlach et al. (2016), the code-share request is processed after the definition of a flight schedule. Code-share is traditionally performed during the tactical phase of the airline planning process, spanning from 12 to 1 month prior to the operation day. The standard goals of code-share are presented in Doreswamy et al. (2017). These agreements are commonly aimed at either improving network coverage by engaging partnerships with airlines operating a complementary network or increasing the frequency of shared flights. The case study included in Doreswamy et al. (2017) analyses a collaborative scenario in the tactical phase of airline planning through the implementation of code-share. The study returns an improvement in revenues ranging from 1.77% to 2.67% depending on the collaboration agreement specifications. However, these results can be considered for the assessment of other collaboration strategies only as a ballpark of the anticipated results and not as a direct term of comparison. In fact, the scope of the paper was to assess the effect of different information disclosure agreements rather than evaluate the impact of novel cooperative strategies.

The literature, however, has not yet fully explored the potential of sharing resources between competitors. Currently, the main collaboration stages are processed repeatedly over a mid-short time horizon of 12-1 months from the day of operation. It is the interest of this project to analyse the potential effects of introducing an additional collaboration phase in an earlier phase with a mid-long time horizon of 18-12 months prior to the date of operation. This novel phase could allow airlines to attain a deeper level of cooperation and, thus, improved efficiency in resource management. The literature showed extensive tools to compute the emissions of single flights and different strategies to optimise the flight path of each flight; however, these tools have not yet been used to guide strategic decisions in the airline planning process. By internalising environmental externalities, it could be possible to not only better capture the impact of flight emissions but also promote to airlines more environmentally thoughtful approaches to operations.

4 Methodology

This chapter presents the methodology adopted to address the central question introduced in the preceding chapter. Firstly, a procedure is designed to gather all the input data, encompassing both the operative inputs and environmental data, including both the emissions and the environmental impact generated. Airlines aim, in pursuit of achieving more environmentally sustainable strategies, to precisely quantify the impact of each flight and subsequently convert emissions into an economic value that encapsulates the diverse effects of various emission species. This value holds both the climate and air quality impacts of the emissions. Subsequently, these inputs are incorporated into the network and frequency planning optimisation linear programming model hereafter described. The environmental costs considered in this model are modulated by the Environmental Taxation Parameter (ETP), which defines how much of the calculated environmental cost is going to be borne by the airlines in the form of taxation. The graphical representation of the core steps in the methodology, as depicted in Figure 2, serves as a visual aid to elucidate the followed process. Each step is described in the following sections of this chapter. The analysis encompasses the collaboration of two airlines, as the potential of the collaboration is not yet defined, and thus it is in the airline's interest to test this cooperative framework on a small scale before expanding it to more airlines. The collaborative actions are performed in an unbiased environment. Supervision by the airlines, or even their direct involvement, can guarantee that biases are avoided in favour of total maximisation of profit and consideration of additional environmental costs.

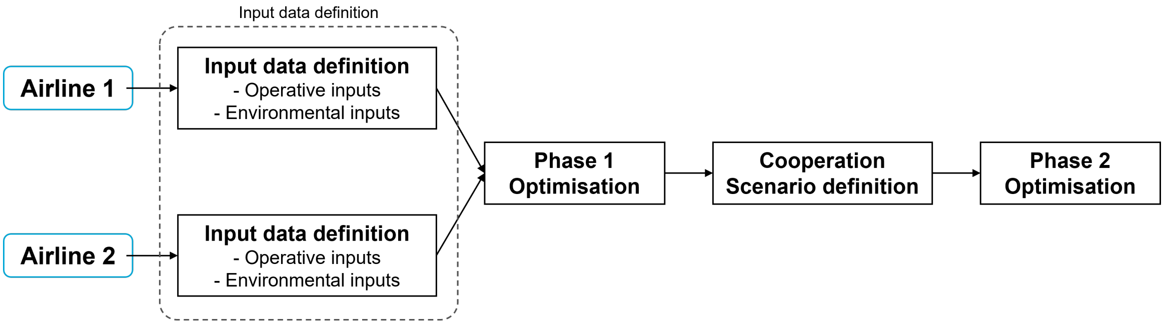

Figure 2: Methodology core steps flowchart.

Before advancing any claims or extending the considerations derived from this model, testing for robustness becomes imperative. This testing process will be achieved through a case study presented in the following chapter. The subsequent sections of this chapter will provide an in-depth description of each step in the methodology, offering clarity and transparency into the research approach. The final considerations should also acknowledge the underlying assumptions made in this model.

The model presented consists of an extension of a network and frequency planning model applied to pure Hub and Spokes airlines, thus bringing along some assumptions:

- The model relies on a static passenger demand estimate. This entails that passenger choices are not affected and do not react to changes in frequencies and connections;
- The two airlines considered are willing to utterly commit to this cooperative effort to achieve improved environmental solutions, entailing that they agree on the possibility of implementing operational changes that could alter their position in the market, thus not evaluating competition among airlines. This assumption also extends to the airlines agreeing on setting up an extended revenue sharing mechanism (not part of this project);
- Ticket fares are not impacted by the addition of new environmental costs or by changes in the network;
- The network and frequency model allows for possible aircraft routing discontinuities.

4.1 Input data definition

The first task undertaken in the methodology is the definition of the data used as inputs. These can be generally grouped into two main groups. The groups are the Operative inputs and the Environmental inputs, as visible in Figure 2.

4.1.1 Operative inputs

Airlines provide a large variety of data. The input required includes "Operative costs", associated with the operational expenses of each flight with different aircraft types; "Flight duration" and "Turn-around time" the time required to complete each flight, including reserved time for turnaround procedures at airports; "Fares", the fare for all Origin-Destination (OD[1]) itineraries within their network, expected "Passenger demand", number of passengers willing to travel from an origin to a destination in the network on an OD basis, "Fleet characteristics", data of their available fleet, including aircraft types, seat capacities, and performance data, and lastly "Network composition", a list of airports reachable with their services.

4.1.2 Environmental inputs

To assess the impact of emissions, it is first necessary to quantify the flight's emissions and, subsequently, evaluate their impact on both the climate and the air quality. The task of quantifying the emissions is fulfilled through the utilisation of the OpenAVEM [Quadros et al. (2022)] software. OpenAVEM operates as a robust tool, proficiently generating a comprehensive 3D emissions map for each flight and consistently accounting for different flight phases and load conditions. Using OpenAVEM, detailed emissions data are obtained per flight, categorised by aircraft type and engine combinations, keeping a fixed load factor of 90%. The emitted species under scrutiny encompass a spectrum of crucial components: carbon dioxide (CO_2), nitrogen dioxide (NO_2), sulphur oxides (SO_x), water (H_2O), carbon monoxide (CO), hydrocarbons (HC), and non-volatile particulate matter ($nvPM$). These species, each possessing distinct environmental implications, collectively contribute to the assessment of the impact of aviation emissions, along with other types such as Contrails which are estimated from the amount of fuel burnt. As the data are to be used in the model by the airlines to estimate what the operation of a flight with a specific aircraft mounting a specific engine would entail environmentally, the focal point is set on standard flight conditions. With the goal of assessing emissions for a standard flight scenario, the airlines rely on a standardised meteorological data set and a fixed load factor. This approach ensures sufficiently accurate estimations of emissions under standardised conditions, facilitating meaningful comparisons across flight scenarios. Leveraging this data set, the airlines can translate emissions quantities into tangible monetary costs. This conversion is facilitated by referencing a conversion table, as elucidated in Grobler et al. (2019), which articulates the monetary valuation of emissions components. Grobler et al. (2019) provides a detailed analysis of how the different species generated impact the environment, providing insights on different flight phases and separating the air quality and climate impact generated. To align with the scope of this project, values pertaining to the full flight phase and encompassing both the climate and the air quality impacts were selected, as such information coincides with the model considered in this methodology analysis. Euros serve as the designated monetary unit of reference in this assessment, with the conversion table, as detailed in Table 6, presented in Euros per kilogram (€/kg). In Table 6, as in the reference paper, the impact on the environment considered is attributed to CO_2, Nitrogen Oxides (NO_x), Contrail, SO_x, Black Carbon (BC), H_2O, Non-Methane Volatile Organic Compounds ($NMVOC$), CO, and Organic Carbon (OC).

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[1] OD represents events originating at the Origin (O) and concluding at the Destination (D), without considering intermediate events.

These are selected to capture the most important aviation-derived factors influencing the atmosphere [Whitelegg (2000)].

Specie	Cost [€/kg]
CO_2	0.0414
NO_x	20.24
$Contrail$	0.0754
SO_x	11.96
BC	56.12
H_2O	0.00230
$NMVOC$	7.084
CO	0.267
OC	10.12

Table 6: Conversion table [€/kg]. Grobler et al. (2019)

The last task undertaken for the assessment of environmental impact is the formulation of the Environmental Taxation Parameter (ETP), applied to the environmental costs of flights. The ETP is a pivotal element in shaping the taxation scheme aimed at fostering environmental protection and collaboration. This parameter serves to modulate the percentage of the additional cost that the airline envisions shouldering as a tax. An ETP of 100% would entail that airlines would fully compensate for the impact that their flight emissions have on the environment.

4.2 Phase 1 Optimisation

In this first optimisation phase, the two airlines establish a collaborative framework. The optimisation tasks can be envisioned as being assigned to an external consulting company or to a division of the two airlines consisting of members from both airlines. In both cases, the airlines would have direct involvement in ensuring an unbiased approach in favour of the maximisation of total profit and of the consideration of additional environmental costs. The collaboration is modelled between two pure Hub and Spokes airlines.

Once all the inputs have been defined, the first phase of optimisation commences. This step of the collaboration agreement consists of mapping a sufficiently large number of collaboration alternatives. In this phase, the Sharing Coefficient (SC) is introduced to represent each airline's willingness to share up to a given percentage of passengers on a given itinerary. The SCs range between 0% and 100%. To compile a sufficiently accurate exploration of collaboration alternatives while also limiting the number of options analysed, the same SC is, in this first stage, applied to all the itineraries of the airline. Each option can be characterised by the combination of a pair of SCs, one for each airline. By setting a step increment of 10% for the SCs for both airlines, it is possible to create an 11 by 11 grid, or more precisely, 121 alternatives overall.

The cooperation is practically implemented in this model in a manner inspired by code-share, albeit with some differences, which marks this cooperative action as a new cooperative step in the planning of the airlines involved. To distinguish the differences, this new approach is defined as "Strategical code-share". The Strategical code-share differs from the standard code-share as the analysis is performed during the strategical planning with a timeline indication of 18-12 months in advance of the day of operations. Moreover, standard code-share is often employed to improve the connectivity of the airline by focusing on agreements with airlines with complementary networks; Strategical code-share is instead focused on improving cooperation on shared itineraries. The cooperation is performed through the sharing of passenger demand from one airline to another. The Strategical code-share does not prevent the application, later in the planning timeline and closer to the day of operation, of the traditional code-share. The model introduces the possibility of future implementation of revenue-sharing mechanisms between the airlines. The model envisions the receiving airline allocating a fifth of the ticket's fare to the supplying airline to symbolically introduce such an option to allow airlines to agree upon appropriate revenue sharing.

The optimisation model employed simultaneously addresses network and frequency planning for both airlines. The specific optimisation model is presented and discussed in Subsection 4.2.1. To fully harness the advantages of this integrated approach, the model also examines options in which passengers take three flights to reach their destination. This eventuality entails passengers changing airlines and transferring through the hubs of the two collaborating carriers. The optimisation returns for each analysed option information on how the solution can be achieved, offering detailed data about the operated flights, their frequency, aircraft types, and the passengers transported within the network.

4.2.1 Model Optimisation - Linear Programming

The optimisation of each collaboration scenario is done through the use of a linear programming (LP) model. In this section, it will be discussed how the LP model is structured while highlighting through the use of mathematical formulation the core aspects of the network and frequency planning LP model.

Sets & Parameters

The parameters and sets employed follow in this section. The numerous items include standard sets, such as a list of airports in each airline's network and the fleet available to the airlines. Through the use of some of these sets, it is possible to avoid the declaration of some unused variables, reduce the number of constraints limiting the solution, and even incorporate multiple variables into a single one, ultimately reducing the total number of required variables.

Sets:

$$\begin{aligned}
A &\longrightarrow \text{Airlines} = [a_1, a_2] \\
N &\longrightarrow \text{List of airports reachable by the airlines} \\
N_a &\longrightarrow \text{List of airports reachable by airline } a \\
H &\longrightarrow \text{List of airlines hubs} \\
h_a &\longrightarrow \text{Hub airport of airline } a \\
L &\longrightarrow \text{Flight Leg segments} = [l_1, l_{2_{12}}, l_{2_{21}}] \\
CA_a &\longrightarrow \text{List of airports closer to } h_a \text{ than to the other airline's hub airport} \\
F^a &\longrightarrow \text{Fleet of airline } a \\
F^a_{ij} &\longrightarrow \text{Fleet type available for airline } a \text{ on flight } ij \\
X &\longrightarrow \text{Set of connections from or to the hubs} = [(i,j,a)\forall a \in A, \forall i \in N_a, j \in N_a | (i \oplus j) = h_a] \\
W &\longrightarrow \text{Set of connections through the airline's hub} = [(i,j,a)\forall a \in A, \forall i \in N_a, j \in N_a | (i \wedge j)_{i \neq j} \neq h_a] \\
Y &\longrightarrow \text{Set of connections through the hubs of the two airlines} = [(i,j,a,l)\forall a \in A, \forall l \in L, \forall i \in N_a, j \in N_a | \\
&\quad ((l \in [1, 2_{12}]) \wedge (i \in CA_a 1) \wedge (j \in CA_a 2))_{a=a_1} \vee ((l = 2_{21}) \wedge (i \in CA_a 2) \wedge (j \in CA_a 1))_{a=a_1} \vee \\
&\quad ((l \in [1, 2_{21}]) \wedge (i \in CA_a 2) \wedge (j \in CA_a 1))_{a=a_2} \vee ((l = 2_{12}) \wedge (i \in CA_a 1) \wedge (j \in CA_a 2))_{a=a_2}] \\
Z &\longrightarrow \text{Set of flights} = [(i,j,k,a)\forall a \in A, \forall i \in N_a, j \in N_a, \forall k \in F^a_{ij} | (i \oplus j) = h_a] \\
M &\longrightarrow \text{Set of transferable itineraries} = [(i,j,a)\forall a \in A, \forall i \in N, j \in N | (i \wedge j)_{i \neq j} \in H \vee (i \wedge j)_{i \neq j} \notin H]
\end{aligned}$$

Parameters:

$$\begin{aligned}
f^a_{ij} &\longrightarrow \text{Airline's } a \text{ ticket fare for itinerary } ij \\
c_{OP}{}^{ka}_{ij} &\longrightarrow \text{Operative flight cost for airline } a \text{ on flight } ij \text{ operated by aircraft type } k \\
c_{ENV}{}^{ka}_{ij} &\longrightarrow \text{Environmental flight cost for airline } a \text{ on flight } ij \text{ operated by aircraft type } k \\
\varepsilon &\longrightarrow \text{Disincentive for passenger share to limit to operated passengers only set to a hundredth} \\
q^a_{ij} &\longrightarrow \text{Demand between } ij \text{ for airline } a \\
b^x_{ija} &\longrightarrow 1 \text{ if } (i,j,a) \in X, 0 \text{ otherwise} \\
b^w_{ija} &\longrightarrow 1 \text{ if } (i,j,a) \in W, 0 \text{ otherwise} \\
b^y_{ijal} &\longrightarrow 1 \text{ if } (i,j,a,l) \in Y, 0 \text{ otherwise} \\
b^H_{ia} &\longrightarrow 1 \text{ if } i \neq h_a, 0 \text{ otherwise} \\
SC^a_{ij} &\longrightarrow \text{Sharing coefficient for airline } a \text{ on itinerary } ij \\
S^k &\longrightarrow \text{\# of seats on aircraft type } k \\
LF &\longrightarrow \text{Load Factor} \\
t^k_{ij} &\longrightarrow \text{Time to operate flight } ij \text{ with aircraft type } k \\
BT^k &\longrightarrow \text{Block time of aircraft type } k \\
AC^k_a &\longrightarrow \text{Aircraft of type } k \text{ in the fleet of airline } a \\
ETP &\longrightarrow \text{Environmental Taxation Parameter}
\end{aligned}$$

Decision Variables

$$\begin{aligned}
x^a_{ij} &\in \mathbb{N} \cup \{0\} & \forall i,j,a \in X &\longrightarrow \text{\# of direct pax between } ij \text{ for airline } a \\
w^a_{ij} &\in \mathbb{N} \cup \{0\} & \forall i,j,a \in W &\longrightarrow \text{\# of connecting pax between } ij \text{ for airline } a \\
y^{al}_{ij} &\in \mathbb{N} \cup \{0\} & \forall i,j,a,l \in Y &\longrightarrow \text{\# of transferring pax between } ij \text{ on leg } l \text{ for airline } a \\
z^{ka}_{ij} &\in \mathbb{N} \cup \{0\} & \forall i,j,k,a \in Z &\longrightarrow \text{\# of flight leg between } ij \text{ operated by airline } a \text{ with aircraft type } k
\end{aligned}$$

$$m_{ij}^{a} \in \mathbb{N} \cup \{0\} \qquad \forall i,j,a \in M \longrightarrow \text{ \# of shared pax on route } ij \text{ by airline } a$$

$$r_{ij}^{a} \in \{0,1\} \qquad \forall i,j,a \in M \longrightarrow \text{ 1 if airline } a \text{ is sharing, 0 otherwise}$$

Objective Function and Constraints

Objective Function, Profit Maximisation:

$$\text{Max}\Bigg[\sum_{ija}^{X} f_{ij}^{a} * x_{ij}^{a} + \sum_{ija}^{W} f_{ij}^{a} * w_{ij}^{a} + \sum_{ijal|l=l_{2_{12}}}^{Y} f_{h_{a_1}h_{a_2}}^{a} * y_{ij}^{al} + \sum_{ijal|l=l_{2_{21}}}^{Y} f_{h_{a_2}h_{a_1}}^{a} * y_{ij}^{al} + \sum_{ijal|a=a_1,l=l_1}^{Y} (f_{ih_{a_1}}^{a_1} + f_{h_{a_2}j}^{a_2}) * y_{ij}^{a_1 l_1} +$$
$$+ \sum_{ijal|a=a_2,l=l_1}^{Y} (f_{h_{a_1}j}^{a_1} + f_{ih_{a_2}}^{a_2}) * y_{ij}^{a_2 l_1} - \sum_{ijka}^{Z} ({c_{OP}}_{ij}^{ka} + ETP * {c_{ENV}}_{ij}^{ka}) * z_{ij}^{ka} - \sum_{ija}^{M} \varepsilon * f_{ij}^{a} * m_{ij}^{a}\Bigg]$$

The Objective Function presents a standard approach of profit maximisation. The considered profit is computed by subtracting from the revenues of all the passengers transported the costs generated by the solution to operate such a network. The function also presents a minor inactivation to share passengers only when the other airline is actually able to transport them; this term does not affect the final calculation of profit as that is directly obtained from operative results. A last note on the Objective Function is how the costs are defined; as can be seen, the costs encompass both the operative costs of the flight, c_{OP}, and the environmental ones, c_{ENV}, opportunely weighted by the ETP.

Subject to:

$$\text{(C1.1)} \quad b_{ija}^{x} * x_{ij}^{a} + b_{ija}^{w} * w_{ij}^{a} + \sum_{a_{TMP}}^{A} b_{ijal}^{y} * y_{ij}^{a_{TMP} l_1} \leq q_{ij}^{a} - m_{ij}^{a} + m_{ij}^{\overline{a}} \qquad \forall a \in A, \forall i \in N, j \in N$$

$$\text{(C1.2)} \quad m_{ij}^{a} \leq q_{ij}^{a} * r_{ij}^{a} * SC_{ij}^{a} * b_{ia}^{H} * b_{ja}^{H} \qquad \forall i,j,a \in M$$

$$\text{(C1.3)} \quad \sum_{a \in A} r_{ij}^{a} \leq 1 \qquad \forall i \in N, j \in N | (i,j,a_1) \in M$$

$$\text{(C2)} \quad x_{ij}^{a} + \sum_{s \in N_a} w_{is}^{a} * (1 - b_{ja}^{H}) + \sum_{s \in N_a} w_{sj}^{a} * (1 - b_{ia}^{H}) + \sum_{s \in N} y_{is}^{al_1} * (1 - b_{ja}^{H}) +$$
$$+ \sum_{s \in N} \sum_{n \in N} \left[y_{sn}^{al_{2_{12}}} * (1 - b_{ia_1}^{H}) * (1 - b_{ja_2}^{H}) + y_{sn}^{al_{2_{21}}} * (1 - b_{ia_2}^{H}) * (1 - b_{ja_1}^{H}) \right] +$$
$$+ \sum_{s \in N_a} y_{sj}^{\overline{a}l_1} * (1 - b_{ia}^{H}) \leq \sum_{k \in F_{ij}^{a}} z_{ij}^{ak} * s^{k} * LF \qquad \forall i \in N, j \in N, a \in A | (i,j,a) \in X$$

$$\text{(C3)} \quad \sum_{s \in N_a} z_{sn}^{ak} = \sum_{s \in N_a} z_{ns}^{ak} \qquad \forall a \in A, \forall n \in N_a, \forall k \in F_{sn}^{a} | (s,n,k,a) \in Z$$

$$\text{(C4)} \quad \sum_{i \in N_a} \sum_{j \in N_a} z_{ij}^{ak} * t_{ij}^{k} \leq BT^{k} * AC_{a}^{k} \qquad \forall a \in A, \forall k \in F^{a}$$

$$\text{(C5.1)} \quad y_{ij}^{a_1 l_1} = \sum_{a \in A} y_{ij}^{al_{2_{12}}} \qquad \forall i \in N, j \in N$$

$$\text{(C5.2)} \quad y_{ij}^{a_2 l_1} = \sum_{a \in A} y_{ij}^{al_{2_{21}}} \qquad \forall i \in N, j \in N$$

The model is subject to eight sets of constraints overall. The first set C1.1[2] ensures that the number of passengers transported on an OD pair is lower or equal to the actual available passenger demand. Differently from a standard demand constraint set, it also encompasses the possibility for the two airlines to have, partially or totally, access to the demand of their industry peers. C1.2 is necessary to limit the number of passengers shared on each route. The limitations include: having access only to what the other airline is willing to share, which cannot be more than what the airline actually has; the possibility to share only in one way with the aid of C1.3 (avoiding pointless shared passengers that return to the original airline); and lastly, the limitation of not allowing passengers to select a connecting flight if they have the option to take a direct flight. C2 ensures that the capacity of the aircraft is respected, making sure that the number of passengers travelling on each route is less or equal to the number of seats available on the same segment. C3 imposes continuity in the aircraft

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[2] The notation $\overline{a}$ is used to refer to the other airline. E.g., if $a = a_1$, then $\overline{a} = a_2$ and vice versa.

network, while C4 verifies that each aircraft type does not get used more than the defined Block Time per aircraft. Lastly, the C5.1 and C5.2 pairs of constraint sets ascertain that the number of passengers travelling through a three-leg itinerary remains constant.

4.3 Cooperation: Scenario Definition

In this step, the airlines define the Sharing Coefficients (SCs), which will form the analysed scenarios. The first phase of optimisation also returns the results for the scenario where no collaboration is considered, thus outlining the "Baseline" scenario when the ETP is set to 0%. Subsequently, the airlines must agree on which coefficients to use to collaborate on a route basis. The airlines use two parallel approaches to define the SCs, envisioning two distinct future scenarios: the first approach consists of minimising the environmental impact generated to define the route-based scenario "R.Env" and the second flows into the second scenario, the route-based scenario "R.Profit" in which the maximisation of profit is prioritised.

To define the SCs, the airlines undergo multiple steps. First, the airlines must define which of the options, obtained from the first optimisation phase, best suits their goal and use it as the starting point for the SCs definition. This step requires the airlines to quantify how attractive they consider each option to be. To achieve this, Formula 1 has been designed. The formula is inspired by a gravitational attraction where the place of the masses is taken by the improvement of a specific parameter compared to its value in the option where no collaboration is considered, and the distance is represented by the difference in how much each airline is sharing. By setting the considered parameter to the variation of "Environmental Cost" it is possible to pursue the definition of the "R.Env" scenario, while if the parameter selected is "Profit" the definition of the "R.Profit" scenario.

$$A^{(a)}_{(SC_i^{(1)};SC_j^{(2)})} = \frac{\Delta z^{(a)} * MD^{(a)}}{\left(abs(SC_i^{(1)} - SC_j^{(2)}) + 1\right)^c} \tag{1}$$

Where $A^{(a)}_{(SC_i^{(1)};SC_j^{(2)})}$ is the attractiveness of the scenario $(SC_i^{(1)}; SC_j^{(2)})$ for airline a, which can either be (1) or (2) for the scenario pair (i, j) from the 11 by 11 grid defined in the first optimisation phase. z is the Key Performance Indicator of which airline a is assessing the attractiveness; thus, $\Delta z^{(a)}$ is the improvement achieved by airline a on that KPI compared to the option where no collaboration is considered. $MD^{(a)}$ is the Market Dominance of airline a defined as

$$MD^{(a)} = \left(\frac{|A^{(a)}|}{|A^{(1)}| + |A^{(2)}|}\right)^{\frac{|A^{(1)} \cap A^{(2)}|}{|A^{(1)} \cup A^{(2)}|}}$$

for which $|A^{(a)}|$ stands for the cardinality of the set of airports in airline a's network, $abs(SC_i^{(1)} - SC_j^{(2)})$ is the absolute difference between the SCs of the two airlines, and c is a numerical coefficient set to 0.5. This formula encompasses various facets of the collaboration between the two airlines. Market Dominance grants more decision-making power to airlines with extensive networks. In contrast, the denominator of the formula is structured to favour options where the difference in the sharing behaviour of the two airlines, relative to their capacity, is minimal.

Airlines then proceed to select the options that maximise the total attractiveness of each option, obtained by summing the individual attractiveness of the two airlines for that option. The analysed KPI, z, differs depending on the scenario being considered; for the "R.Env", z takes the value of the savings achieved over the "Environmental Costs" KPI, thus positive values for a decrease in environmental impact, while for the "R.Profit" scenario, the value z is set to the increment in profit generated, referencing the "Profit" KPI.

After having identified this starting point, the airlines assess for each route which option, among the ones obtained with the first optimisation phase, maximises the aspect considered for that specific route. The aspects considered are always the minimisation of environmental impact costs, for the "R.Env" scenario, and the maximisation of profit for the "R.Profit" scenario. This step of the definition of SCs on a route basis is done by employing Equation 1. Using the information obtained by performing this assessment, the airline is able to modify the SCs of the initial option. Lastly, after having defined the SCs on a route basis for both the "R.Env" and "R.profit" scenarios, the model proceeds to run the final optimisation.

4.4 Phase 2 Optimisation

After having defined the SCs for all the routes, the model runs a final optimisation, which will return the results for the "R.Env" and the "R.Profit". The optimisation model employed to perform this last task is shared with the one employed in the first optimisation phase, presented in Subsection 4.2.1. The results encompass several aspects of the solution, including Key Performance Indicators (KPIs) to assess the performance of the considered scenarios under different aspects. The KPIs returned can be gathered into three main categories: the Operational indicators (Total number of Passengers, Number of passengers taking direct flights, Number of passengers taking connection flights, Number of passengers shared, Number of flights, Number of destinations connected, Number of filled seats, Overall seat capacity, and Load Factor), the Environmental indicators (CO_2, NO_2, H_2O, and Fuel burnt), and the Economic indicators (Profit, Revenue, Operative Costs, and Environmental Costs, Environmental costs per passenger). Furthermore, each scenario's results also provide information on how the solution can be achieved, offering detailed data about the operated flights, their frequency, aircraft types, and the passengers transported within the network.

5 Description of the Case Study

A pragmatic case study is instituted to validate the model and assess the potential of this type of collaboration. The model focuses on the collaboration framework between environmental taxation and airline profitability. Within this framework, the potential for collaboration between two prominent carriers: KLM, the Royal Dutch Airlines (Koninklijke Luchtvaart Maatschappij), and TAP, the flag carrier of Portugal, is evaluated over a simulation horizon of a week. For simplicity of reference, the International Air Transport Association (IATA) codes "KL" and "TP" will be employed henceforth. It is important to note that while the data were gathered from real-world sources, the primary objective does not entail a direct comparison between the findings and real-world solutions; rather, the "Baseline" scenario is generated as a reference.

The optimisation processes can be conducted using the commercial solver Gurobi, which can then be implemented within a Python model. Due to the expanded complexity of the problem and the inherent re-iterative nature of the selected method, to expedite the calculation phase, the optimality gap parameter is set at 1% for each simulation. To further enhance simulation temporal efficiency, the complete hardware architecture can be leveraged via multiprocessing. This entails distributing tasks across individual computational cores. As a result of these strategies, an entire set of 121 simulations can be successfully executed on a standard laptop equipped with 8 computational cores, achieving completion within approximately 5 hours.

5.1 Airlines Selection

In this section, the rationale behind the selection of airlines is elucidated. To construct an efficacious case study and recognise the profound influence that input data can exert on the ultimate outcomes, a deliberate decision was made to seek real-world data. This endeavour was undertaken with the aim of establishing a realistic framework to guide the analysis and ensure the credibility of the results.

The airlines ultimately selected for this study are KL and TP, as previously mentioned. The rationale behind this selection arises from the model's inherent design for a pure Hub and Spokes (H&S) network, with KL boasting a network topology closely aligned with this configuration. Following the selection of the initial airline, it was imperative to choose a second airline that shared similarities with KL to foster an equitable collaborative scenario. After a comprehensive evaluation, TP emerged as the second airline of choice. TP, akin to KL, exhibits a network topology that approximates an H&S network. Additionally, both airlines maintain international networks, comprising 163 destinations for KL and 93 for TP, with a substantial overlap of 57 common destinations, thereby facilitating the implementation of a significant collaboration. Furthermore, it was ensured that both airlines could provide a comparable level of service quality to their customers. This assurance underpins the assumption that passengers will choose to fly without significant preference for either airline, thereby ensuring equitable conditions for the collaboration. Once the airline selection process was completed, data pertaining to the operated fleets was generated based on the real-world fleet compositions of the two carriers (sourced from Flightradar24 (2023)).

Airline	AC Name	Number	Seats	Engine	Haul
KL	A332	6	268	CF6-80E1A3	Long
KL	A333	5	277	CF6-80E1A3	Long
KL	B737	8	142	CFM56-7B22	Short
KL	B738	31	180	CFM56-7B27	Short
KL	B739	5	189	CFM56-7B26	Short
KL	B772	15	316	GE90-94B	Long
KL	B773	16	408	GE90-115B	Long
KL	B789	13	275	GEnx-1B	Long
KL	B78X	8	318	GEnx-1B76A	Long
KL	E190	25	100	CF34-10E5	Short
KL	E195	15	132	PW1921G	Short
KL	E170	17	88	CF34-8E5	Short
TP	A320A	11	174	LEAP-1A26	Short
TP	A321A	22	216	LEAP-1A	Short
TP	A319	6	132	CFM56-5B5/3	Short
TP	A320B	13	186	CFM56-5B4/P	Short
TP	A321B	3	216	CFM56-5B3/P	Short
TP	A332	3	269	CF6-80E1A4	Long
TP	A339	19	298	Trent7000-72	Long
TP	E190	10	110	CF34-10E7	Short
TP	E195	7	120	CF34-10E7	Short

Table 7: Fleets input details

5.2 Data-set definition and validation

In this subsection, an overview is provided of the systematic generation of all data sets crucial to the case study. It is important to note that the utilisation of real-world data inherently supports the credibility of the research, aligning with established industry standards. To commence, OAG Data, encompassing historical passenger demand records from the year 2019, was provided as the foundational data set [Birolini et al. (2021)]. The set is composed of Origin-Destination (OD) data. To reduce variability within the data set, data points reflecting passenger demand lower than 30 were intentionally excluded. This exclusion, accounting for approximately 5% of the total passenger demand, was made while preserving the data set's integrity. The actual fleet composition of the two selected airlines was sourced from Flightradar24 (2023). Furthermore, comprehensive aircraft data, including seat capacity and engine specifications, were retrieved from Airfleets (2023), ensuring the reliability and authenticity of the information. Data are presented in Table 7. The determination of ticket prices followed a regression procedure. A training data set from Skyscanner (2023), representing the year 2024 for the considered destinations, was employed. Through a regression model, fare prices (F) were calculated, distinguishing between short-haul (SH) and long-haul (LH) flights based on the flight OD distance (D). The regression equations took the form of Equation 2 for SH and Equation 3 for LH, with a corrected R^2 value of 0.73.

$$F_{SH} = 0.0397 * D + 135.17 \text{ €} \tag{2}$$

$$F_{LH} = 0.0074 * D + 857.07 \text{ €} \tag{3}$$

To ascertain flight operating costs, reference was made to the work of Swan and Adler (2006). The cost (C) formulas were contingent on flight distance and the number of seats (S) on the aircraft. For SH flights, the formula used is Equation 4, while for LH flights, it is Equation 5.

$$C_{SH} = (D + 722) * (S + 104) * 0.019/1.08 \text{ €} \tag{4}$$

$$C_{LH} = (D + 2200) * (S + 211) * 0.0115/1.08 \text{ €} \tag{5}$$

The ETP is initially set at 100% of the total environmental cost. This decision is based on the willingness of considered airlines to reach net-zero emissions by 2050 [Air France-KLM group (2021)]. To capture more precisely the effect of this taxation-like approach, the case study is re-iterated with different ETPs, namely [0%, 50%, 100%, 200%], to perform a sensitivity analysis. The emission impact costs are obtained by leveraging specific engine characteristics data from BADA 3.15 provided by Eurocontrol (2023) to perform precise analysis on the emission with OpenAVEM. Lastly, the parameters of daily aircraft utilisation time, or block time (BT), set at 10 hours, the load factor (LF), established at 90%, and turn around time (TAT), set to 30 min, were chosen in accordance with prevalent industry practices, as supported by MIT (2021).

6 Results

In this chapter, the outcomes for the three scenarios considered in the case study presented in Chapter 5 are discussed. A subsection is dedicated to each scenario, these being "Baseline", "R.Env", and "R.Profit". In the subsection dedicated to the "Baseline" an analysis of the robustness of the model and its evaluation. Although the model generates an extensive array of results, the focus lies on presenting the most significant findings. The model analyses both participating airlines, KL and TP, simultaneously; the overarching conclusions are drawn from the collective outcomes. The performances are assessed through different KPIs, which can be grouped into three main areas encompassing economic, operational, and environmental data, as described in Subsection 4.4.

6.1 "Baseline" scenario

The "Baseline" scenario results are fundamental to define a common comparison basis to evaluate the performances of the different scenarios. The "Baseline" is defined as a representation of the current situation, or, in other words, what can be currently achieved without the introduction of any novel strategical collaboration agreement and of precise consideration of the environmental impact generated by the flight emissions, thus setting the ETP to 0%. In Table 8 the KPIs for the results of the "Baseline" are presented.

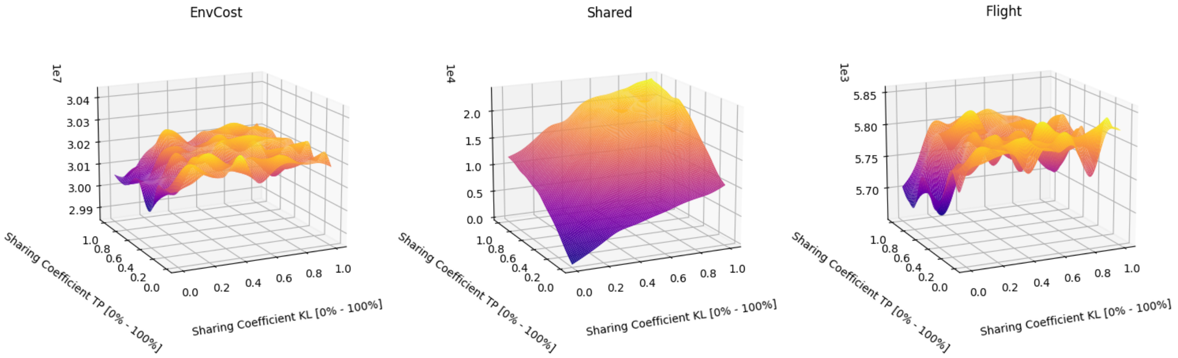
Model robustness

By analysing the intermediate result generated in the first optimisation phase, it is possible to assess the robustness of the optimisation model with the KPIs considered. Making use of Graphs 3 representing the variation of some of the main KPIs for different collaborative options considered in the first optimisation phase, it is possible to assess the robustness of the optimisation model. The graphs presented reference the intermediate

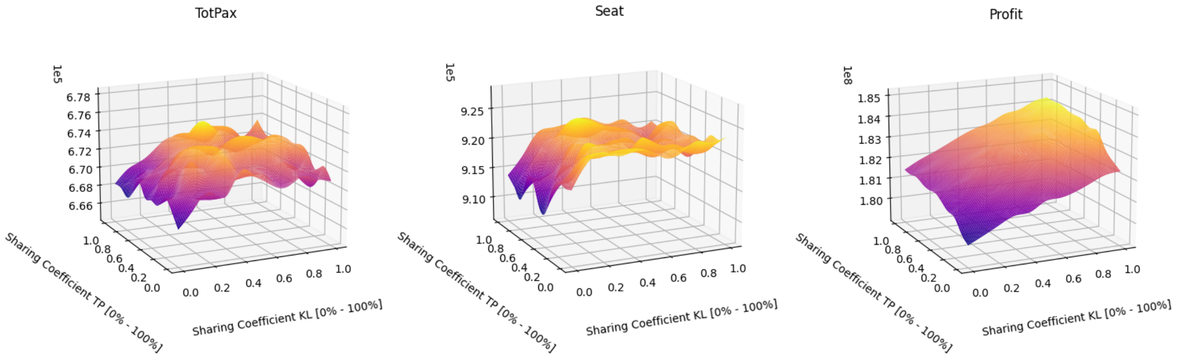
Scenario	Baseline
Profit [€]	1.80E+08
Revenue [€]	2.50E+08
OpCost [€]	7.01E+07
EnvCost [€]	3.02E+07
Fuel [kg]	5.10E+07
CO_2 [kg]	1.61E+08
NO_x [kg]	9.37E+05
H_2O [kg]	6.31E+07

Scenario	Baseline
TotPax	6.68E+05
Shared	0
Env/Pax [€]	45.15
Flight	5786
Destinations	245
FilledSeat	8.23E+05
AvailableSeat	9.18E+05
LF	89.59%

Table 8: Result for "Baseline" scenario. Performances combined for the airlines for main economic, operational, and environmental KPIs.



(a) Environmental Costs (b) Passengers shared (c) Flights



(d) Total passengers (e) Seat Capacity (f) Profit

Figure 3: 3D Plots of the variation of some KPIs obtained for ETP 0% with different collaboration options after the first optimisation phase.

solutions without added environmental costs. The considerations made are, however, applicable to all the results obtained, as no significant difference emerges for any of the ETP considered.

Graphs, such as in Figure 3(f), depict that the model returns sufficiently robust results and these present a small variability, this also allows a trend predictability over the various collaboration scenarios. This characteristic is also identifiable in the number of passengers shared among the two airlines, as can be seen in Figure 3(b), verifying the hypothesis that an increasing number of passengers are shared when fewer restrictions are imposed and thus showing that there is an underlying benefit in setting up a collaboration agreement.

On the other hand, other results, such as the total number of flights (Figure 3(c)), intrinsically connected to the indicator of seat capacity (Figure 3(e)), the total number of passengers served (Figure 3(d)), and the environmental costs (Figure 3(a)), do not show the same level of robustness. These indicators show an increasing trend with collaboration, as it happens for profit, but, differently from it, they show higher variability and unpredictability in the results. All the simulation results obtained with different ETPs share such trait. This type of variability can be attributed to the greediness of the model, which, in order to maximise profit, maximises the exploitation of resources. As will be later shown in the result analysis, the average load factor stays nearly constant and close to its maximum value throughout all the scenarios. Another example of resource exploitation can be seen in the total number of passengers operated, which reaches an average of 88% of the total available demand, also showing little variation throughout the different scenarios. The model's greediness can be imputed for the results that do not show a significant trend related to collaboration but rather smaller variations among scenarios.

For the aforementioned reason, the results that are employed to extract and generalise conclusions on the effect of collaboration are limited to the indicators that ensure sufficient robustness, such as the profit generated. For the remaining indicators, generalisation of conclusions on the effect of collaboration is not advised without the adequate modification of the optimisation model to reduce its greediness. To ensure the general reliability of the results and to aid the reader in having a better understanding of the results, a variability analysis is included.

To measure the variability of results, using the results from the "Baseline" scenario as reference points, it is computed the relative variation of the considered scenarios. This returns a variability range over the considered scenarios, presented in the following sections. This approach facilitated a more precise assessment of the effects arising from all the introduced innovations. The ranges are presented in Table 9.

KPI	Variation range
Load Factor	[-0.09%, 0.20%]
Destinations number	[-0.41%, 0.41%]
Environmental Cost	[-1.99%, 0.21%]
Tot. Pax	[-0.14%, 0.87%]
Seat Capacity	[-1.01%, 0.37%]
Number of flights	[-2.14%, 0.10%]
Time flown	[-1.94%, 0.63%]
Fuel Consumption	[-1.78%, 0.32%]

Table 9: Variation ranges of KPIs across scenarios using "Baseline" as reference.

The first parameter considered is the average load factor. This metric is calculated as the mean of individual load factors, computed for each flight segment by dividing the filled seats by the available seats. The variation in load factors is minimal across scenarios. The analysis also encompassed an evaluation of the variation in the number of destinations served. The range presented in Table 9 corresponds to a variation in absolute terms of $[-1, 1]$ destination. Interestingly, this analysis could be expanded by observing the relative change for each airline. KL showcases a range of $[0, 1.29\%]$ and TP $[-1.11\%, 0]$, or respectively $[0, 2]$ and $[-1, 0]$ in absolute terms. Additionally, it was executed a comprehensive analysis of changes in the number of flights operated by both airlines. It's noteworthy that these ranges shrink when the number of flights gets compared with the alternatives without the possibility of collaboration with the same ETP later shown in Subsection 6.1. Ranges for $ETP = [0\%; 50\%; 100\%; 200\%]$ respectively become $[-0.61\%, 0.10\%]$, $[-0.63\%, 0.42\%]$, $[-1.22\%, +0.45\%]$, and $[0\%, 0.78\%]$. To assess variations in aircraft utilisation time, or time flown, it is necessary to compute the average variation per aircraft type across the selected scenarios. Considering airlines on an individual level, the analysis revealed a relative range of variation in utilisation time for KL's fleet of $[-0.44\%, +0.12\%]$, while TP's fleet exhibited a broader range of $[-5.08\%, 1.71\%]$.

General conclusions and considerations of the effectiveness of collaboration can be drawn from the different results for profit. The effect on other indicators, such as the total environmental impact, can be assessed on a local scale, and final consideration can be based on evaluated scenarios.

Model evaluation

As the model incorporates simplifications and relies on assumptions, it becomes challenging to seek a direct conformity between the model and real-world data. Moreover, the model presented in this document adopts a novel approach to network planning with collaboration, making it less straightforward to validate through comparisons with external sources, whether real-world data or prior research.

Nevertheless, it is possible to make a relative comparison with the observed improvements presented in Doreswamy et al. (2017). In that study, a collaboration between two airlines resulted in a 1.71% increase in revenue gains. However, it's crucial to acknowledge that significant and distinctive differences exist between the model presented in the referenced paper and the one introduced in this document. As described in Section 3, the case study presented by Doreswamy et al. (2017) is focused on assessing the effect of different levels of maturity in sharing information, making use of traditional code-share as a collaborative agreement, thus applied on a tactical level in a short- to mid-term horizon of 12-1 months prior to the day of operation. This makes a direct comparison unreliable for robust model validation. Instead, it primarily serves to establish that the order of magnitude of the improvement achieved falls within the same ranges, supporting the plausibility of the results obtained.

To further evaluate the model, it is analysed to what extent the results obtained for the "Baseline" scenario can be traced back to the solutions achieved in the real world. This comparison must acknowledge the assumptions introduced by the model presented in the paper. The first indicator that can be considered is the list of destinations connected, returned for the "Baseline". The number of destinations in the "Baseline" has an overlap with the input data of 96%. By analysing the frequency of flights obtained in the "Baseline" solution, it is possible to make a comparison with the real schedule retrieved. By taking a sample of 50 airports randomly selected, it emerged that on average, the solution retrieved by the model underestimates the actual frequency, processed from FlightConnections (2023), by an average of 1.92 flights, with a mean squared deviation of about 4.41 flights. Lastly, it is possible to compare the percentage of the passenger demand fulfilled; for the "Baseline" scenario, this amounts to slightly more than 87% of the original passenger demand. The ranges point at the likelihood for the results to be a sufficiently close representation of a real-world situation; thus, contemplating the limitations imposed by the assumptions and simplifications of the model, it is possible to consider the model to be successfully validated.

"No collaboration" alternatives

To expand the array of reference alternatives, a set of options is included, which represents alternatives in which only the additional environmental costs are considered, without including any possibility for collaboration. These alternatives can be retrieved from the first optimisation phase by selecting the option with both SCs set to 0. Notably, the "No collaboration" obtained for an ETP of 0% corresponds with the "Baseline" scenario presented in this section and is used as a common comparison basis. These results will be employed in the overall comparison to expand the analysis of the results.

Scenario	**No Collaboration**			
ETP	0% ("Baseline")	50%	100%	200%
Profit [€]	1.80E+08	1.65E+08	1.50E+08	1.21E+08
Revenue [€]	2.50E+08	2.50E+08	2.50E+08	2.49E+08
OpCost [€]	7.01E+07	7.03E+07	7.01E+07	6.92E+07
EnvCost [€]	3.02E+07	3.00E+07	3.00E+07	2.96E+07
Fuel [kg]	5.10E+07	5.08E+07	5.08E+07	5.01E+07
CO_2 [kg]	1.61E+08	1.60E+08	1.60E+08	1.58E+08
NO_x [kg]	9.37E+05	9.31E+05	9.31E+05	9.21E+05
H_2O [kg]	6.31E+07	6.29E+07	6.28E+07	6.20E+07
TotPax	6.68E+05	6.70E+05	6.69E+05	6.65E+05
Shared	0	0	0	0
Env/Pax [€]	45.15	44.76	44.81	44.57
Flight	5786	5760	5752	5644
Destinations	245	246	244	244
FilledSeat	8.23E+05	8.24E+05	8.23E+05	8.15E+05
AvailableSeat	9.18E+05	9.20E+05	9.18E+05	9.09E+05
LF	89.59%	89.57%	89.63%	89.61%

Table 10: Result for alternatives without collaboration. Performances combined for the airlines for main economic, operational, and environmental KPIs.

6.2 "Route Environment" scenario

The scenario "Route Environment", or "R.Env", represents the core result obtained within this paper. The airlines collaborate to reduce the environmental impact their operations have. The absolute values for the KPIs of the "R.Env" scenario are shown in Table 11.

These results can be better analysed by comparing each of the KPIs with the results of the "Baseline" presented in Table 8. This comparison is presented in Table 12 by showcasing the relative change with the "Baseline" results.

As can be seen from the relative changes, "R.Env" consistently yields solutions with increased revenues while also improving the environmental impact of the solution. A more detailed effect of different ETPs will be analysed in the overall analysis presented in the following section; however, it can be seen that an environmental improvement can be achieved with the collaborative approach aimed at reducing emissions impact already in the ETP 0% case. The environmental impact reduction that is foreseen for a full consideration of environmental costs, ETP 100%, reaches 1.33%.

Notably, the profitability of the results is highly impacted by the introduction of additional costs, showing a substantial decreasing trend. This is within the expected results as it is not foreseen by the model to modify the

Scenario	**R.Env**			
ETP	0%	50%	100%	200%
Profit [€]	1.81E+08	1.66E+08	1.51E+08	1.23E+08
Revenue [€]	2.51E+08	2.51E+08	2.51E+08	2.52E+08
OpCost [€]	7.00E+07	7.00E+07	6.96E+07	6.93E+07
EnvCost [€]	3.01E+07	2.99E+07	2.98E+07	2.96E+07
Fuel [kg]	5.08E+07	5.07E+07	5.04E+07	5.01E+07
CO_2 [kg]	1.60E+08	1.60E+08	1.59E+08	1.58E+08
NO_x [kg]	9.35E+05	9.30E+05	9.24E+05	9.18E+05
H_2O [kg]	6.29E+07	6.27E+07	6.23E+07	6.19E+07
TotPax	6.70E+05	6.71E+05	6.68E+05	6.67E+05
Shared	4.91E+03	6.58E+03	9.04E+03	1.11E+04
Env/Pax [€]	44.89	44.66	44.54	44.31
Flight	5746	5724	5682	5662
Destinations	246	246	244	245
FilledSeat	8.20E+05	8.21E+05	8.17E+05	8.14E+05
AvailableSeat	9.17E+05	9.16E+05	9.12E+05	9.09E+05
LF	89.51%	89.55%	89.58%	89.57%

Table 11: Result for "R.Env" scenario. Performances combined for the airlines for main economic, operational, and environmental KPIs.

Scenario	**R.Env (relative change)**			
ETP	0%	50%	100%	200%
Profit [€]	0.45%	-7.69%	-15.83%	-31.54%
Revenue [€]	0.27%	0.39%	0.28%	0.78%
OpCost [€]	-0.20%	-0.24%	-0.82%	-1.22%
EnvCost [€]	-0.23%	-0.71%	-1.33%	-1.99%
Fuel [kg]	-0.27%	-0.55%	-1.17%	-1.78%
TotPax	0.33%	0.38%	0.03%	-0.14%
Env/Pax [€]	-0.57%	-1.09%	-1.36%	-1.86%
Flight	-0.69%	-1.07%	-1.80%	-2.14%
Destinations	0.41%	0.41%	-0.41%	0.00%

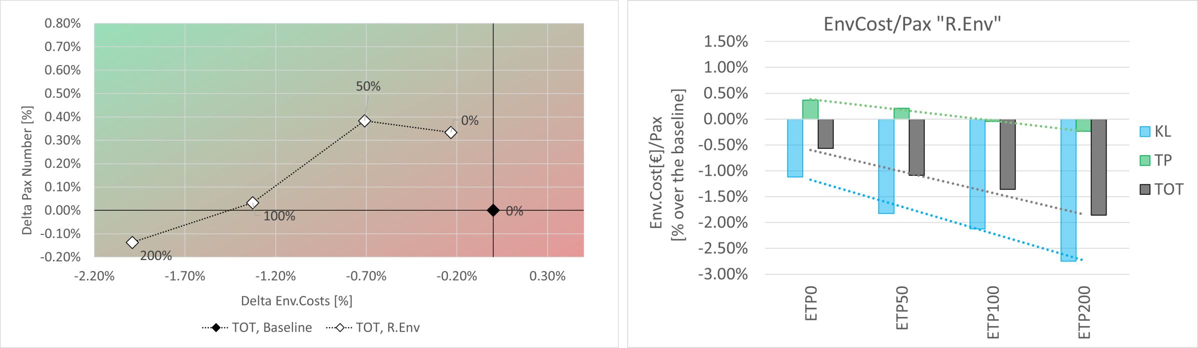
Table 12: Relative change in "R.Env" results over "Baseline".

fares to reflect the novel costs, which are by definition self-imposed. This implies that airlines can commit to the improved environmental solution without necessarily remitting the total monetary amount. By evaluating the alternative in which airlines are not compelled to shoulder the environmental costs of their emissions but still follow the approach applied for the "R.Env" scenario, they could achieve an increment in profit of 0.71%, when considering an ETP of 100%, or up to 1.32% when using an ETP of 200%. This result can be computed by deducting the environmental costs from the profit and confronting it with the "Baseline". This proves that such a type of collaboration is an effective method to reduce the impact of taxation on profit; however, the amount is not sufficient to utterly counterbalance its effects. It is advisable for airlines to adopt this cooperation structure along with other measures to completely balance this type of environmental taxation.

The analysis of the environmental performance of the "R.Env" scenario can also be paired with the analysis of the total number of passengers transported. This paired analysis, shown in Figure 4(a), showcases that applying the approach used for the "R.Env" returns generally improved results for both the emissions (decrement in emissions considered as improvement) and total number of passengers. To aid the reader in understanding the graph, a gradient emphasises the improvement obtained by getting closer to the left-top corner.

In Figure 4(a), the results from the "Baseline" are used as a reference. The results graphically depict the general improvements achievable by following the solution proposed by the "R.Env" scenario. Regardless of the ETP considered, all the alternatives can be found on the left side of the vertical axis. Noticeably, through the implementation of collaboration, it is possible to pair the reduction of emissions with a higher number of passengers transported, implying a higher efficiency achieved. This is possible thanks to the relocation of passengers to more sustainable alternatives, made possible by the exploitation of the two airlines' combined fleet. Having more spacious aircraft in terms of seats is an effective strategy to accommodate passenger demand originating from the collaborative peer; moreover, it is witnessed that having access to more demand on specific flights could make worth the increment in frequency of the given flights, opening the possibility of accommodating passenger demand that was not previously considered.

By investigating more into the operational solutions provided for the "R.Env" it can be seen that passengers are mainly shared by TP to KL. In fact, the Dutch airline showcases a higher ability to adapt to a higher number of passengers without necessarily increasing the number of flights or overall emissions. This characteristic is not shared by the Portuguese airline, which always commits to a trade-off in terms of passengers transported and emissions. A more detailed analysis of the performance of the two airlines will follow in the overall analysis.



(a) Graph of "R.Env" scenario on KPIs combined. Environmental costs and total number of passengers transported.

(b) Average environmental cost per passenger in "R.Env" scenario.

Figure 4: Graphical representation of KPIs: environmental costs, passengers and their ratio for the "R.Env".

The general improvements observed in Figure 4(a) are numerically confirmed in Figure 4(b), which showcases the average environmental cost per passenger transported both for the airlines individually and for the overall solutions. For all the ETP alternatives in the "R.Env" scenario, the total environmental cost per passenger improves compared to the baseline, and a noticeable improvement trend emerges as the ETP considered increases.

6.3 "Route Profit" scenario

For the "Route Profit", or "R.Profit", scenario, the airlines collaborate to maximise their profitability. The absolute values for the KPIs of the "R.Proift" scenario are shown in Table 13.

These results can be better analysed by comparing each of the KPIs with the results of the "Baseline" presented in Table 8. This comparison is presented in Table 14 by showcasing the relative change with the "Baseline" results.

As can be seen from the relative changes, "R.Profit" proposes solutions that prioritise the maximisation of profit. When compared with the relative results of the "R.Env" the profitability anticipated by the "R.Profit" is higher, showcasing an additional 1.28% of profit on average. The revenue indicator is also significantly higher than the "R.Env". On average, the revenue obtained by following the approach of the "R.Profit" is 2% higher than the "Baseline". The lowest anticipated revenue is obtained for the alternative, in which the ETP is set to 200%. This aspect is reasonably justified by having costs, which make specific itineraries no longer worth to be flown. In accordance with this analysis, it can also be seen that the number of flights decreases when focusing only on highly profitable routes with high capacity, as the number of passengers transported can still be expected to be slightly higher than what can be achieved for the "Baseline". The "R.Profit" scenario emphasises the ability of the modelled collaboration agreement to propose an improved solution specifically for the profitability of the airlines. By comparing the anticipated profits deducted from the environmental costs with the "Baseline" scenario, the results point at the possibility of achieving an incremented profit of up to 2.21% for the consideration of an ETP of 100%.

A similar evaluation to the one carried out for the "R.Env" where multiple KPIs, for environmental savings and the number of passengers transported are evaluated in pairs, can be performed for this scenario. The paired analysis, shown in Figure 5(a), displays the potential effects of applying the approach of "R.Profit". In this scenario, the environmental savings are significantly more contained when compared with the results of "R.Env", yet generally still positive. It is highlighted how these results point to solutions with a heightened number of passengers transported, reflecting the improved revenue gain of the alternative analyses. The same scale for the graph's axis is preserved to allow a direct comparability with Figure 4(a). Notably, the solutions for the "R.Profit" are all placed closer to the vertical axis while being shifted to the top.

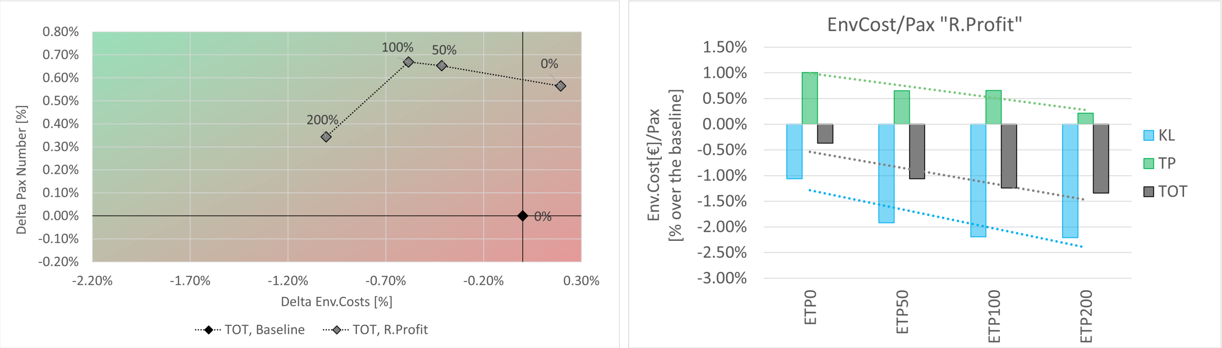
The relative increment in the number of passengers is nearly twice the one achieved for the "R.Env". This heightened number of passengers is the main reason for the general improvement in efficiency over the average environmental costs per passenger shown in Figure 5(b). For all the ETP alternatives in the "R.Profit" scenario, the total environmental cost per passenger improves compared to the baseline, and a noticeable improvement trend emerges as the ETP considered increases.

Scenario	**R.Profit**			
ETP	0%	50%	100%	200%
Profit [€]	1.84E+08	1.69E+08	1.54E+08	1.24E+08
Revenue [€]	2.55E+08	2.55E+08	2.55E+08	2.54E+08
OpCost [€]	7.05E+07	7.05E+07	7.05E+07	6.99E+07
EnvCost [€]	3.02E+07	3.00E+07	3.00E+07	2.99E+07
Fuel [kg]	5.11E+07	5.09E+07	5.09E+07	5.06E+07
CO_2 [kg]	1.61E+08	1.61E+08	1.61E+08	1.60E+08
NO_x [kg]	9.39E+05	9.32E+05	9.30E+05	9.27E+05
H_2O [kg]	6.33E+07	6.30E+07	6.30E+07	6.26E+07
TotPax	6.72E+05	6.72E+05	6.72E+05	6.70E+05
Shared	1.83E+04	1.78E+04	1.81E+04	1.80E+04
Env/Pax [€]	44.98	44.67	44.59	44.54
Flight	5792	5784	5778	5688
Destinations	246	245	245	245
FilledSeat	8.24E+05	8.25E+05	8.25E+05	8.18E+05
AvailableSeat	9.19E+05	9.19E+05	9.19E+05	9.12E+05
LF	89.69%	89.77%	89.76%	89.72%

Table 13: Result for "R.Profit" scenario. Performances combined for the airlines for main economic, operational, and environmental KPIs.

Scenario	**R.Profit (relative changes)**			
ETP	0%	50%	100%	200%
Profit [€]	2.13%	-6.18%	-14.45%	-30.99%
Revenue [€]	1.94%	1.97%	2.00%	1.74%
OpCost [€]	0.52%	0.48%	0.49%	-0.37%
EnvCost [€]	0.19%	-0.41%	-0.58%	-1.00%
Fuel [kg]	0.32%	-0.07%	-0.16%	-0.73%
TotPax	0.56%	0.65%	0.67%	0.34%
Env/Pax [€]	-0.37%	-1.06%	-1.25%	-1.34%
Flight	0.10%	-0.03%	-0.14%	-1.69%
Destinations	0.41%	0.00%	0.00%	0.00%

Table 14: Relative change in "R.Profit" results over "Baseline".



(a) Graph of "R.Profit" scenario on KPIs combined. Environmental costs and total number of passengers transported.

(b) Average environmental cost per passenger in "R.Profit" scenario.

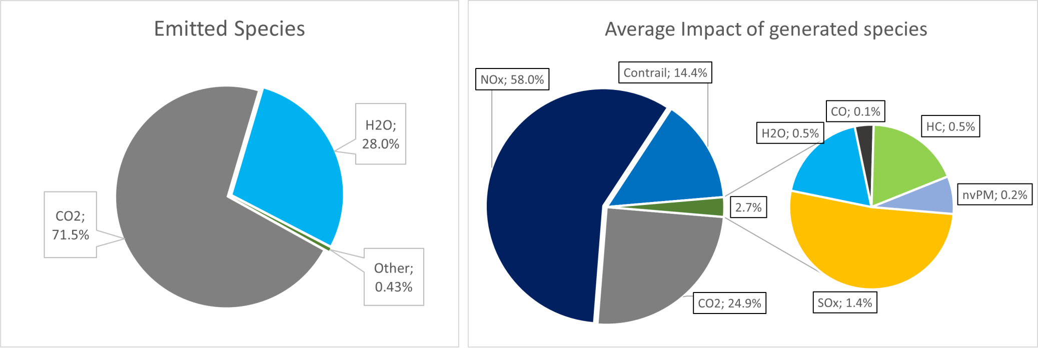
Figure 5: Graphical representation of KPIs: environmental costs, passengers and their ratio for the "R.Profit".

6.4 Overall results analysis

The results obtained through the applied methodology provide valuable insights into the impact of considering additional environmental costs and exploring collaborative strategies on the network and frequency planning process to improve the environmental impact and preserve the economic sustainability of airlines.

Emissions considerations

An overall analysis commences by providing a more comprehensive environmental analysis of the solution. An assessment is made regarding the proportions of various emissions species in relation to the total emissions generated during operations. The results of this analysis are presented in Figure 6(a), which displays the average values derived from all potential flight combinations. Additionally, a second pie chart, as depicted in Figure 6(b), illustrates how the total environmental impact can be attributed to different species of emissions.



(a) Emitted Chemical Species.

(b) Environmental Impact generated.

Figure 6: Average emissions and relative Environmental Impact.

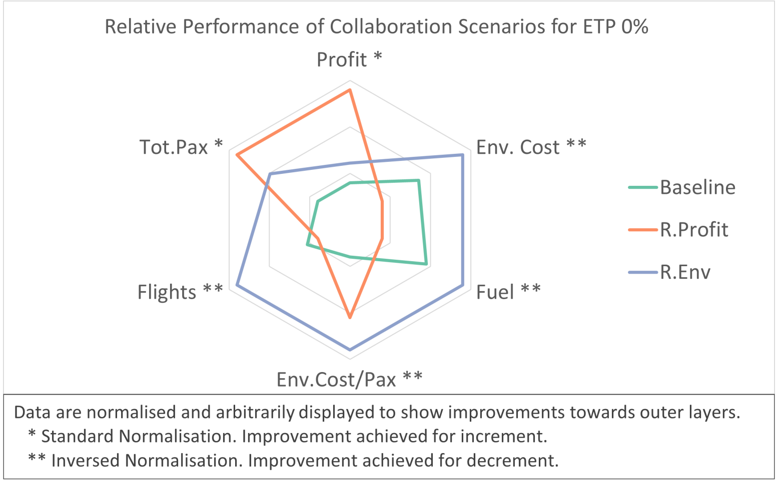
The pie charts encompass average emissions results as the different scenarios did not return relevant differences regarding the distribution of emissions, thus making the average emissions valuable for enhancing the general comprehension of the emission distribution generated and their impact. The application of collaborative strategies and introduction of environmental externalities in the strategical planning did not affect significantly the distribution of the different species and the impact they generate. An intriguing observation emerges when examining the emissions profile. While carbon dioxide (CO_2) accounts for more than two-thirds of the total emissions in kilograms during the emission phase, its overall impact on both air quality and climate diminishes to less than a fourth of the total impact. Simultaneously, it becomes evident that the social cost of nitrogen oxides (NO_x) emissions, owing to their substantial impact on air quality and their high emissions during the initial and final phases of the flight, supersedes other emissions species in terms of total impact. NO_x emissions independently represent more than half, precisely 58.0%, of the total social cost.

Operational considerations

A first analysis of the effects of collaboration among KL and TP can be done by comparing the performances of the "R.Env", "R.Profit" and "Baseline" scenarios obtained for simulations where no additional environmental cost is accounted for. Referring to Figure 7 it is possible to witness the normalised performance of these selected scenarios over six different KPIs. To highlight the improvement obtained for each KPI, the normalisation has been reversed for the indicators of Environmental Impact Costs (Env.Cost), Fuel consumption (Fuel), average environmental cost per passenger (Env.Cost/Pax) and number of flights (Flights). The normalisation has been inverted to showcase an improved performance of the scenario for a reduction in such categories. The Profit and Total number of Passengers (Tot.Pax) make use of a the standard normalisation. For graphical purposes, the normalisation range has been shifted upward by 0.4 equally in all scenarios. The adaptive normalisation allows to easily read the graph. It is evident that the "R.Env" scenario outperforms the "Baseline" scenario on all the indicators considered, as its line completely includes the baseline. Interestingly, by selecting different criteria as the "R.Profit", the collaboration can also yield improved profitability and a higher efficiency, compared to no collaborative action, for environmental cost per passenger. The improvement in the last parameter can be attributed to the steep increase in passengers transported.

This trend remains stable throughout all different ETPs, with the only exceptions being the number of passengers in "R.Env" over "NoCollab" and the number of flights for ETP 200%. This can be attributed to the higher efficiency achieved with the increase in the taxation parameter; when the environmental costs are evaluated to double their actual impact, not having collaboration agreements forces the two airlines to reduce the number of flights to the ones that are more profitable. Collaboration proves to be a valid alternative to preserve the capabilities of the network without sacrificing the environment.

In this section, an analysis of results specific to airlines is also presented to provide more depth to the analysis of the results. This introduces an additional perspective beyond the collective consideration of airlines. It is imperative to acknowledge that variations in input data exert a significant influence on the ultimate outcomes. Analysing the results obtained by KL and TP at the end of the second optimisation phase, disparities



Data are normalised and arbitrarily displayed to show improvements towards outer layers.
* Standard Normalisation. Improvement achieved for increment.
** Inversed Normalisation. Improvement achieved for decrement.

Figure 7: Normalised performances of collaboration scenarios (in range [0.4, 1.4] for graphical purposes) for ETP 0%.

emerge between the two airlines, likely originating from both network structure and fleet composition. These discrepancies result in responses that are similar, but not entirely overlapping, in various scenarios.

The Portuguese flag carrier gains considerably from receiving passengers from the collaborating airline. The capacity to accommodate more passengers translates into enhanced profitability. However, it is crucial to note that achieving this heightened passenger volume entails a reliance on less environmentally efficient solutions for TP, as corroborated by the graphical data representation in Figure 8. This figure illustrates, similarly to Figures 4(a) and 5(a), the relative deviations from the "Baseline". The figure also includes the total results for all the alternatives of "R.Env" and "R.Profit" for reference. It is apparent that alternatives involving higher passenger transport by TP also coincide with heightened environmental costs. Notably, no options fall within Quadrant II, underscoring the trade-off between increased passenger transport and elevated environmental costs.

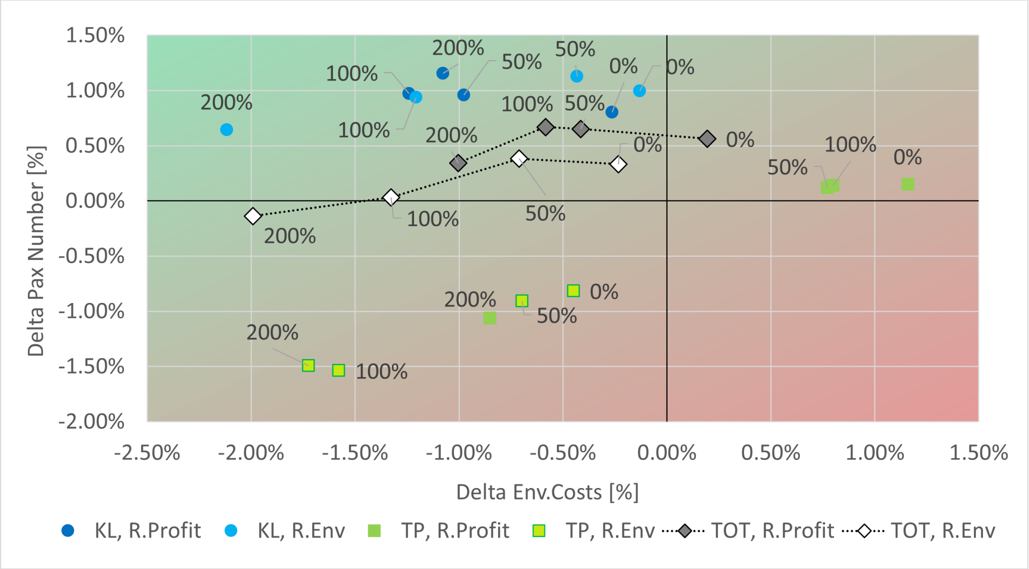


Figure 8: Graph of Environmental costs and total number of passengers transported KPIs combined for both "R.Env" and "R.Profit" with insights on individual airlines.

The graphs in Figure 8 unveil a notably distinct situation for KLM. The Dutch airline not only experiences an upsurge in the number of passengers across all the examined scenarios but, perhaps more significantly, it consistently operates with a reduced environmental impact when each scenario is compared to the "Baseline" scenario featuring no environmental cost consideration.

A contrast is evident between the two airlines when analysing the environmental cost per passenger shown in Figures 4(b) and 5(b), with KL showcasing a consistent improvement, signifying an increase in efficiency, while its counterpart, TP, exhibits non-always negative results. This counter-intuitive outcome can be explained by considering that overall efficiency consistently improves, underscoring the general enhancements attained through the implemented measures.

KL is able, in all the scenarios considered, to increase the total number of passengers transported without necessarily sacrificing environmental impact. On the contrary, TP does not show this ability. This can be attributed to the larger size of the airline and the higher number of aircraft types available, making it more likely for KL to find an alternative solution capable of integrating a higher number of passengers when these are available on a selected route. By analysing deeper the "R.Env." scenario, it is possible to notice that KL receives passengers predominantly on long-haul flights; KL's fleet shows a significantly higher average seat capacity on aircraft types destined for such flights. A practical example can be seen when KL is able to introduce 2342 available seats on long-range flights by only adding 6 new long-range flights, despite the average seat per aircraft being 329 (1975 new seats for 6 long-range flights). KL is able to achieve this higher effectiveness by having more options in its fleet, which allows it to adapt the seat capacity more proactively based on the amount of passenger demand. TP, on the contrary, only has two aircraft types predisposed for long-range flights, which offer an average seat capacity of 284; more than 45 seats difference than KL's.

A comparable insight emerges for "R.Profit" results, where on long-range destinations, KL is generally preferred, while TP demonstrates the precedence on shorter-range flights. Consistently with the consideration just made for long-haul flights, even if TP and KL have both six different aircraft types for these destinations, TP's fleet has on average 26 more seats available on a single short-haul flight, giving it an advantage in such destinations. Even if the results point to the general consideration that higher capacity results in more effective coverage of passenger demand, the limitations of the model impose a refrain from extending such consideration to a broad level. Moreover, this aspect highlights the greediness of the model, which considers a static demand, as it is well documented that achieving a higher flight frequency is often preferable to having fewer, more spacious flights to capture passenger preferences.

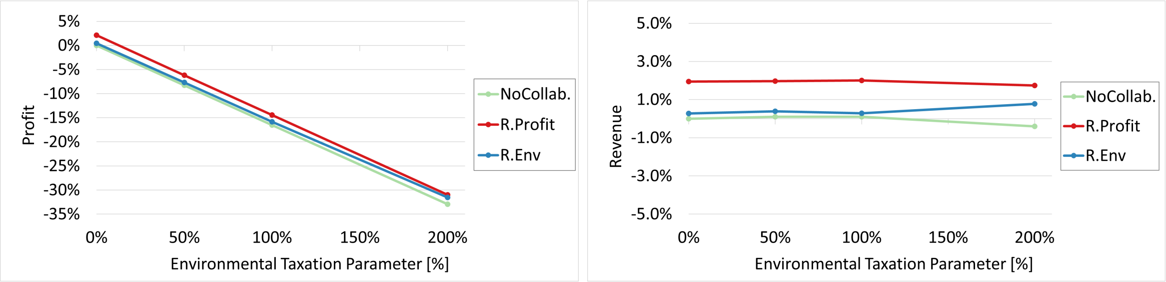
Considerations over the effects of ETP

Another relevant analysis that can be done on overall solutions is the effect that the ETP has on various indicators. The graphs in Figure 9 present a clearer visualisation of the ETP's influence on the indicators. The set of results pertaining to solutions where no collaboration is considered, namely "NoCollab." introduced in Subsection 6.1, is included as a reference. All the results are always expressed as relative changes over the "Baseline" scenario.

In these graphs, one can observe the effects of the ETP on the various selected scenarios, also shedding light on the relationships among the "NoCollab.", "R.Env", and "R.Profit" scenarios within this case study. Evidently, a linear decline in profit becomes apparent with increasing consideration of the environmental impact of operations. In Figure 9(a) it is possible to assess the considerable effect on profit of the introduction of environmental taxes. The profit decrement reached by setting the ETP to 100%, when compared with the "NoCollab." scenario and ETP 0%, has a considerable value of -16.52% if no collaboration is allowed, -14.45% for the "R.Profit", and -15.83% for the "R.Env". Recalling that these outcomes are obtained for static passenger demand and fixed fare prices, it would be possible to foster more stable solutions for the airlines' profitability by allowing such factors to vary. This phenomenon holds true for both airlines combined and separately at a similar rate. The steep decrement in profit can be directly imputed to the stable and linear increment of the total cost shown in Figure 9(c). Operative costs, however, do not show a clear trend, and it is only possible to point at a general marginal decrement for ETP 200%; confirmed by the related indicators of the number of flights and total number of passengers, which show comparable trends (Figures 9(e) and 9(f)). This entails that the additional costs come from the additional environmental taxation. It is worth noting that in Figure 9(a), all the considered scenarios show a higher profit than what is achieved in the "NoCollab.". "R.Profit" is significantly higher than the other two, while the gap with the "R.Env" scenario decreases towards higher ETPs. This entails that it is possible to increase the ETP only to a certain factor, after which differences between scenarios will diminish significantly; this would likely happen as the number of sustainable options available both on the economical and environmental sides would decrease substantially.

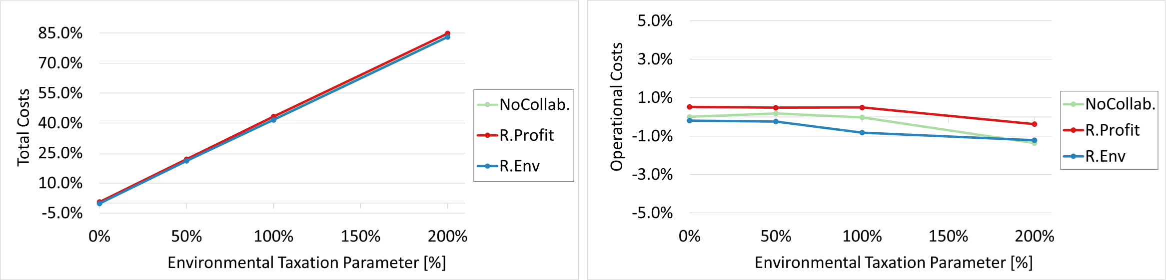
The variation of ETP did not show a significant effect on neither the Revenue nor the Load Factor of the solutions. As can be seen from Figures 9(b) and 9(j), these indicators do not show a significant change, and the data distribution does not point to any evident trend. Surprisingly, there is no evident correlation between the number of passengers transported and the revenue generated. This limited unrelatedness is only apparent as the revenue is directly generated by the passengers transported, but points to marginal changes in the distribution of passengers.

It is noteworthy that for all ETP values considered, the "R.Env" scenario returned results with higher profits and lower emissions footprints in relation to the "NoCollab.". This aspect can be seen in Figures 9(g) and 9(a) and has a direct correlation with the fuel burned, as depicted in Figure 9(i). This points to employing the collaboration not only as a strategy to limit the impact of taxation on the financial side of the airlines but also as a potential virtuous approach to the environment. "R.Env" serves as a clear example of a scenario where the airlines, fully shouldering the environmental impact cost of their operations, are able to achieve a 1.33% reduction of environmental impact when compared with the current situation or a 0.75% when compared with



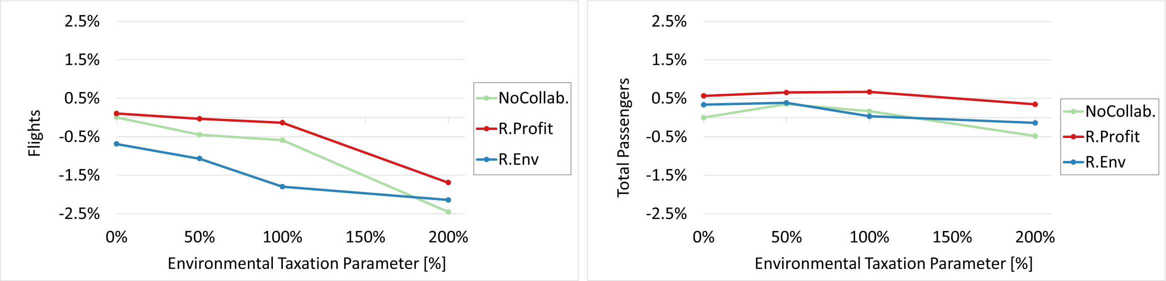
(a) Profit.

(b) Revenue.



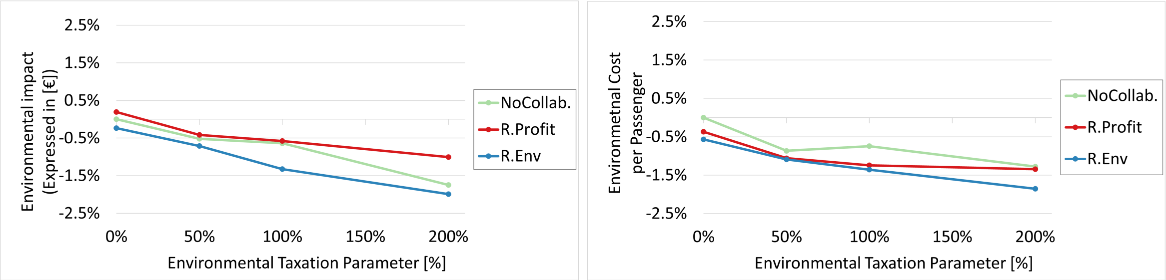
(c) Total Costs.

(d) Operative Costs.



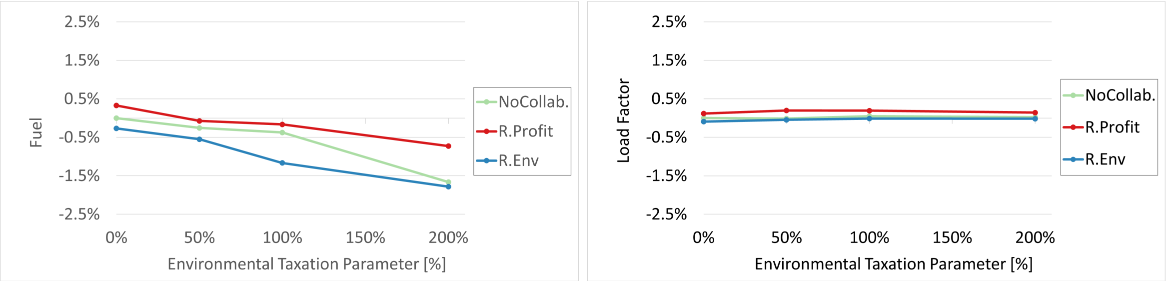
(e) Flights.

(f) Total Passengers.



(g) Environmental Impact.

(h) Environmental Cost per passenger.



(i) Fuel Burn.

(j) Load Factor

Figure 9: Effect of different ETPs on various KPIs.

the same ETP scenario with no collaboration while still increasing the profit (even if slightly) by 0.82%.

Nevertheless, it is evident that the ETP has an impact on the emission levels of the airlines, as depicted in Figure 9(g). The increment of the ETP results in a monotonically decreasing trend for the environmental impact. Averaging "R.Env" and "R.Profit", it is possible to achieve a 0.96% improvement (a decrease in absolute impact in relation to the "Baseline") on the environmental impact of the two airlines by setting an ETP of 100%. The effect of the taxation scheme is limited yet consistent throughout all the scenarios considered (net reduction of environmental impact observable in all scenarios). This aspect is extremely important as it assesses the ability of the airlines to affect their strategic decisions through a taxation-like scheme by selecting more environmentally friendly solutions. Taxation schemes based on emission impacts could well suit the promotion of other environmental measures such as fleet renovation, the employment of Sustainable Aviation Fuels, etc. The model defined in this project could easily incorporate such additions through the re-definition of individual flight environmental costs. The other KPI related to the environmental impact of the airline in relation to the number of passengers transported also shows a down-trending slope. Remarkably, this trend, as can be seen in Figure 9(h), is denoted by a significant initial drop and a subsequent stabilisation of the indicator. It appears that it would be possible to compromise on a lower taxation scheme while still achieving substantial improvements in the average environmental cost per passenger transported.

7 Conclusions

In this concluding section, the core question that has driven this project is revisited. The primary aim was to assess the potential of collaboration between two Hub and Spokes service airlines in reducing the environmental impact they generate with their flight operations.

The cooperative efforts of two airlines are implemented through an agreement to share passenger demand among industry peers and to foster collaboration through the inclusion of a taxation-like system for the environmental impact of emissions. This novel collaboration phase is foreseen to be applied during the Strategical planning phase with the Network and Frequency planning model described in the methodology.

The tangible effects that airlines can achieve through collaboration and by shouldering the costs of environmental impacts generated by flights are analysed. The effects are evaluated not only from an environmental perspective but also from the airlines profitability point of view. To evaluate the potential of this approach, several steps have been defined throughout the methodology.

Firstly, emissions data per flight were calculated while accounting for the variability arising from different aircraft types and engine configurations. This data set enabled the assessment of the environmental impact of the emissions, thereby furnishing the airlines with a quantification of the environmental impact of their operations and, thus, a better understanding of the potential outcomes of a taxation-like scheme. In this preliminary phase, airlines also produce operative data such as fare prices, passenger demand, flight operative costs, etc. The methodology then instructs to perform a Network and Frequency Planning optimisation. The linear programming model implemented follows the indications of including novel environmental taxation and the possibility to share passenger demand on common routes.

The second phase of the methodology sees the airlines decide the collaboration specifications for each route to foster environmental savings or profitability. This collaboration effort is then followed by a second round of optimisation, which returns the airline's operative solutions to align with their goals.

The model is analysed through the effects of a full taxation case study that considers two selected airlines, KL, the Dutch flag carrier, and TP, the Portuguese flag carrier, that participate in this cooperative endeavour. Within this collaborative framework, airlines are given the flexibility to prioritise different aspects, including environmental impact ("R.Env") or profit ("R.Profit).

The results observed from the presented case study underscore the potential benefits for the environment of establishing a taxation-like scheme in which airlines shoulder the cost of the environmental impact of flights. The reduction in environmental impact achieved is 1.33%; this figure, though seemingly limited in absolute terms, carries profound implications. The analysis reveals that such a taxation scheme, with such considerable effects on profit, could serve as a catalyst for broader innovation within the aviation industry. It could encourage the adoption of alternative approaches, including Sustainable Aviation Fuels, fleet modernisation, and more, all of which align with the broader goal of reducing aviation's environmental footprint. The model introduced would effortlessly adapt to these new operative data, as the results showed consistency in the beneficial effects on the environment of the taxation measure.

The results are sufficiently robust to derive overarching insights into the impact of collaboration on profitability. The results indicate that further modifications to the model are advisable to extend consideration to other operational indicators at a more general level. The robustness of the model allows for extended consideration of the central question of the collaboration's potential as a tool to preserve airline profitability. The findings demonstrate that a collaborative approach to network and frequency planning consistently yields improved profits. On average, collaborating airlines can anticipate a profit increase from a 0.71% when prioritising environmental savings up to a 2.21% when prioritising profitability. While this improvement alone may not fully offset the effects of a more substantial taxation scheme, it underscores collaboration as a viable tool for mitigating not only the financial implications of taxation but also for enhancing profitability under standard conditions without additional taxation. Collaboration in this manner consistently proved effective in providing extra profitability when compared with scenarios where taxation was imposed but no collaboration was implemented. Moreover, through collaboration alone, ETP 0%, airlines can strategically adopt a virtuous approach while also addressing their environmental impact. Collaboration emerges as an effective means of enhancing the profitability of participating airlines. It is essential to recognise that, to effectively counteract the potential ramifications of a taxation scheme with significant environmental implications, collaboration must be complemented by other additional measures.

In summary, the study focuses on the potential benefits of collaboration while emphasising the instrumental role of an environmental taxation-like system in the aviation industry. These findings underscore the need for an approach that combines collaborative efforts and other innovative strategies to ensure the sustainability of the aviation sector in a world increasingly concerned with environmental impact and financial viability.

8 Future Work

This study has provided consistent evidence of the effectiveness of collaboration in mitigating environmental and financial challenges in aviation while also paving the way for the implementation of new features. The model could seamlessly integrate a redefinition of the cost function and change the objectives of the collaboration agreement. The identified potential obtained for the introduction of this additional collaborative stage in the airline planning process points at promising avenues for future exploration and refinement. Another potential direction is to expand the scope of collaboration to involve more than two airlines under the same taxation scheme and collaborative framework. This could yield even more substantial improvements. Additionally, integrating Sustainable Aviation Fuels (SAFs) into the model could enhance its environmental impact. The adoption of more efficient and environmentally friendly aircraft types, such as electric or hydrogen-powered planes, offers another avenue for improving the industrys sustainability. This could be easily implemented by computing how these differences would impact operative costs and environmental externalities. Another step forward can be achieved by transitioning from static to dynamic demand modelling, thus providing deeper insights into passenger preferences and decision-making and further enhancing the models accuracy. Finally, the development of advanced revenue-sharing mechanisms could encourage more extensive collaboration among airlines and improve overall outcomes. In conclusion, while this study has shown positive results, it also lays the groundwork for further research, promising greater environmental and financial benefits in the aviation industrys future.

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II

Literature Study

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1

Introduction

In this initial chapter, the structure of this document will be presented while outlining the project areas of research. It includes a brief presentation of the thesis project, for which this study serves as literature study, to motivate the relevance of each covered topic and how they relates to the overall scope of the study.

The scope of the thesis project, that includes this literature study in it, is to evaluate the potential environmental impact reduction that modifications in the network planning phase of an airline have. In more detail the hypothesis on which the project is built is that it is possible to obtain an improved environmental impact by an internal and external, through the collaboration with other airlines, reallocation of resources during the network planning phase. In this evaluation, the principal considered resources are passengers demand and fleet components. The founding idea of the project is that it is possible to increase environmental efficiency of the service provided by airlines without expecting a forced decrement in revenues. This project is aimed at evaluating the actual entity, if any, of the effects obtainable with modifications to the current methodology. This projects advances the hypothesis that a significant environmental improvement can be obtained by including a cooperation phase in the early strategical planning period of the airline, with a particular focus on the network planning decisions. This entails that involved players must be willing to commit to a certain degree of change in both their internal and external resource management policies.

In Chapter 2, is presented an in-deep analysis of which approaches have been proposed in the literature to provide a solution to the challenging task of network planning. The literature section, which this chapter comprises a review of, covers both the practical aspect of airline's strategical decision making systems and the cooperation strategies that have been researched. In this comparison are considered, not only the different approaches to the problem but also, the different programming strategies that are used to solve such problem. This evaluation entails that all the variations in what parameters, factors, players and simplifications are to be critically analysed. From this chapter it will emerge what approach to the problem and what solution techniques best suits the project. It will also provide sufficient evidence to support the proper selection of parameters to be included in order to balance the overall complexity and quality of the model to be implemented.

In Chapter 2 the literature regarding how the data concerning the passengers demand between locations can be generated is also evaluated. In this section, it is again necessary to gather information on different ways such data can be generated. Each of these methodologies is critically analysed also by considering the feasibility and accessibility of each data source. It is not unusual for these data to be hidden behind paywalls or being not fully disclosed. This section will guide the reader in the understanding of every decision to be taken in the data creation process to provide realistic, and not necessarily truthful, data. Such data will serve as foundation for the environmental impact evaluation, overall scope of the project.

To evaluate the change in the environmental impact produced by the modification in operations introduced by the novel methodology it is necessary to define a quantification procedure for such variation. In Chapter 3 the different approach found in the literature will be evaluated and compared. At the end of this chapter, it will emerge what type of impact should be considered, how this is generated and how it can be quantified to best represent the scope of the project. This analysis includes a detailed explanation of the different level at which the problem can be considered and what are the implication of each layer. The level of complexity and detail of the retrieved models are critically analysed to understand the benefits of each, what can be reused and which considerations have not yet been investigated. At the end of this chapter it will emerge which methodology, to evaluate environmental impact, best suits this project scope and how this can be implemented.

Lastly, to ensure a correct interpretation of the document, it is relevant to clearly state that this study is intended for a knowledgeable and well versed audience in the topics hereafter covered. Hence, introductions to the theoretical frameworks behind the fields covered are not included in this document as they are assumed to be already within the readers' areas of competence. For this reason, the theoretical introductions will be limited to providing enough context information to ensure a clear readability of the document.

2

Airline Operations

This chapter aims at presenting to the reader the literature study performed to answer the research questions related with the operational side of the project. For each topic it is presented an augmented explanation of the relevance of it for the achievement of the final scope of the project.

In Section 2.1, the reader is presented with the context on the airline operational aspect with a focus and correlated explanation on the topic that will be analysed in the following sections. It is also included the methodology followed to gather the relevant literature.

In Section 2.2, a brief history of the research achievement in the field of Airline's Network Planning will be presented. For the task covered by the project there is a dedicated section which includes the relevance of the specific task, Section 2.3.

Similarly, in Section 2.4 the tactical phase of the airline decision process is covered. This section focuses specifically on the schedule planning tasks.

In Section 2.5 the literature regarding the possible ways of cooperation between airlines is reviewed. This section is structured to identify which collaboration agreements best suit the scope of this project. This section contains dedicated subsections to analyse the different aspect of cooperation. The collaboration between two entities such as two airlines intrinsically involves both economical and legal aspects. Even if these are not directly included in the area of interest of the project, the related literature is reviewed in Section 2.5.1 as the practical implication of these fields can not be overlooked. Finally, in Section 2.5.2 the historical evolution of code share in the aviation sector is covered.

Lastly, the different solution techniques developed in the literature to tackle the challenge are analysed.

The chapter is concluded with a summary of the findings previously described.

2.1. Context

The general architecture of the airline planning decision process was established over time. From early stages, such structure was divided in distinct phases which theoretically differed in the timeline, or how long in advance that particular task should have been performed. Early task definition included network definition, schedule planning, fleet planning, dispatching and routing as can be seen in [61].

The division is mainly theoretical and it went through several evaluations during the years. In [6] the main tasks are presented as: Schedule design, fleet planning, aircraft maintenance routing and crew scheduling. It is interesting to note how the maintenance and the consideration of crew as a resource increased with time as can also be seen in the similar structure presented in [19].

A more updated division can be found in several publications. [72] hereby cited as an example. The modern structure defines three major sections: Strategy Planning, Tactical Planning and Operation Planning. Each section is comprised of different sub tasks. Each task is generally part of one of the three major phases and they have different time horizons, it is not impossible, however, for them to overlap in the timeline, making the division mainly an organisational and/or theoretical label.

In this literature study the subsections of Network Planning, part of the Strategic Planning that spans from ten to one year before the day of operation, and the Schedule Planning, part of the Tactical phase that approximately goes from one year to one month in advance, are explored for their relevance for the project's scope.

Differently from the methodology later shown in Chapter 3, where a unique query is used to scan the relevant literature, for this section it has been decided to use a backward snowballing method. Relevant literature reviews found among previous publications where used as starting point for this search. These paper are: [19], [25], [74], [10], [37], and [11].

2.2. Strategic Planning

The long term planning of an airline includes several steps. In this project, it is considered that existing airlines collaborate; for this reason, strategic decisions prior to the airline establishment are not included in the evaluation.

These antecedent choices have been described in detail in the literature. One of the first consideration that an airline must go through is a market analysis to understand how they can permeate the market. The answer to this first question gives a first indication on what type of service the airline could provide.

Another extremely impactful element in the creation of an airline is the location of its main operation hub. The geographic location has a direct impact on the airline, not only due to the global reach of aviation but also, because it determines the potential reach to customers in the neighbouring area. Politics, law and taxation must also not be overlooked when evaluating such decision. The literature has been prolific on these topic in the previous decade while gradually shifting its interest for hub location to other newcomers in the global system of commercial transportation (online delivery to have an example) ([2], [13], [3] and [66]).

However, it is not always the case for airlines to have full control over these choices. As described, many internal and external factors condition the choice of the type of service provided. Nonetheless, it has been observed that airlines' services tend to resemble either a Point-to-Point or an Hub-and-Spoke. The characteristics of each can be found in the table provided on page 91 of [16]. In [5], the authors proposed an index based comparison method to determine how close to either of the two architectures the airlines were.

These aspects of the airline process are not going to be considered directly in the thesis, yet the collaborating airlines are to be selected taking into consideration the effects of these differences.

Following the timeline in the airline process, the next phases are the ones that are considered in this novel collaboration process proposed in this project.

2.3. Network Planning and Passengers Demand Forecast

This phase is necessary to decide which connections are going to be covered by the airline and also often includes a fleet composition strategy. Deciding with large advance is fundamental when planning for resources such as aircraft that traditionally entail large investments, long-term financial impacts and long-term effects on operations ([12] and [58]).

The analysis on network planning has been codified throughout the years; however, since the optimisation process highly relies on demand forecast data, the combination with a dynamic demand is a challenge that is yet to be efficiently solved.

An intuitive approach to demand forecasting has been presented in [2]. In the paper, the forecast is origin and destination based and it employs the population, the GDP (Gross Domestic Product) and the distance as variation factors. The paper also includes a parameter to distinguish the belonging of either the origin or the destination to the EU.

In the same period, [71] proposed another take on demand calculation. The authors extended the considered parameters to the frequency provided by the airline for the considered flight, the number of spokes that could be reached with a connecting flight and the average fare. The additional parameters considered where selected by the authors based on the outcomes of the study published the previous year by the same authors: [70]. In this antecedent study the authors also confirmed the validity of the S-curve effect of service frequency on market share.

The literature gathered showed a widespread use of gravity models to estimate the passengers demand. In [16], it is pointed out that these models had a long history in representing volume of attracted passengers for markets outside aviation and a book from the year 2010 is cited to show the adoption of this model via a first refinement for aviation purposes ([22]).

After the definition of the gravity model, a previously overlooked aspect, demand variation, became no longer trivial. The variation in passengers demand started to grow in terms of interest by both the academic and business worlds. This led to the introduction of concept such as spillage and spoilage to consider passengers responses to given airlines operative choices.

In [52] this concept of demand uncertainties is further explored by using a scenario tree where the eventuality of different volume of demands are considered to optimise the fleet planning of the airline. Another paper expands the evaluation on demand forecast is [9]. In this paper, the authors investigate the gravity model assumption of having independent origin and destination pairs.

In recent years, the literature has introduced the concept of exploiting the tight correlation between demand forecasting and Network and Frequency Planning. This approach aims to address both tasks using a single overarching model, reflecting the interconnection between these strategic planning phases within an airline. By doing so, it offers improved solutions that closely align with real-world scenarios, considering how changes in one area affect the other. An example of this integrated approach can be found in [10]. The study employs a detailed gravity model to estimate passenger demand, which is then fed into an iterative network planning optimisation model which affects the original demand.

The objective of this paper of capturing the passengers demand variability in the Network Planning phase of the airline perfectly aligns with the scope of the thesis project. The approach proposed in [10] will serve as starting point for further evaluations.

2.4. Schedule Planning

Moving closer to the day of operation, around one year prior, it becomes necessary to develop a more precise timetable for the network. This is crucial to start the ticket sale. For the scope of this project the timetable generation is a fundamental step to define precisely which, when and how often the flights are to be performed and by what type of aircraft. Having this information will then allow for the final climate impact assessment.

Generating the full airline schedule is a large problem that has been the focus of several past researches. Due to its complexity the schedule generation challenge has traditionally been divided into a sequence of smaller problems to allow for a more manageable size of the problems ([7]). Main sub problems that are necessary are fleet assignment, aircraft routing and passengers flow problem.

As the interest of this study is to have complete data set on the aircraft operating a given network to quantify the related emissions, this literature review focuses on the first step in the schedule generation.

To begin the fleet assignment problem it generally needed to define a network. [79] define two standard ways to accomplish this goal. The first approach proposed is by setting up a connection network, first introduced in 1989. In the paper it is stated that each airport has two timelines for departure and arrival; the network makes use of three different type of arcs (flight, connection, and original/terminal). The second model commonly used is the time and space network (TSN) . This second approach also uses three types of arcs; namely flight, ground, and night. The authors state that the core difference between the two approaches consists of a trade off between the model size and the information obtained from the model. The time and space network was seen to outperform the connection network when the number of flight considered begun to increase. As for the analysis made in this project are based on a large scale network, the time and space network is preferred.

Formulations of the TSN can be found in several documents. [21] defined a primitive TSN to create a schedule to be used later for the actual scheduling of the airline. [45] also uses a structured TSN to develop the schedule while attempting to combine the fleet composition problem with the fleet assignment.

A recurring pattern observed in the literature is the initial independent research on each problem, followed by subsequent attempts to enhance solutions by integrating various sub-tasks. For instance, [69] developed a timetable from scratch and further integrated considerations of competition from other airlines and passenger choices into their model. Another noteworthy paper investigating improved supply-demand interaction is [10], which bases flight scheduling on a TSN.

Once the network has been generated, it is possible to assign the airline's fleet to it. This is commonly done trough the fleet assignment. There exist several variation of it. [60] presented the basic Fleet Assignment Model (FAM) to solve the problem and several variations that combine this solution strategy with other key aspects of the airline's planning. A relevant variation introduced is the Itinerary-based FAM (IFAM) where itineraries are used instead of single flights ([79], [61]). The FAM has some underlying limitation as it requires to have a known demand and assumes the flying times to be fixed and known ([6]).

In the scope of this project an attempt will be made to overcome the limitation linked with the necessity of having defined demand data as previously discussed; however, the flight duration will not be focus of analysis and average data from the industry will be used as standard input.

2.5. Cooperation between airlines

Airlines can cooperate on different aspects and on different layers of their operations. The scope of collaborations between business organisations can span in large range. A collaboration consists of an interaction between the participants that partially or totally share a common interest. The interaction relies on the information exchange between the participants. It must, however, not be overlooked the importance of sharing data in a competitive sector such as the aviation one.

[50] identifies and labels three main way in which the information can be shared. These labels are White, Gray and Black which respectively represents how precise and complete the information is transferred going from utter disclosure, to partial, and ending with little knowledge being transferred.

[73] well presents that having an incomplete transmission of information can result in added complexity and sub-optimal results. For the scope of this study it is conceptualised as all the data shared by the participants to the collaboration are managed by a external entity with no interest in the transferred data outside the scope of the cooperation agreement. Using this approach it is possible to work with a White strategy, which means that all considerations can be performed under the assumption that information are being disclosed completely.

A different approach to information sharing in airlines collaboration can be found in [23] that labels three stages as Speech (availability exchange for marketing), Sight (complete itinerary sharing), and Split (dynamic revenue allocation) with an incremental level of maturity of integration. This method is disregarded because it deemed as not relevant for the scope of this project to implement a more sophisticated communication strategy that would increase the level of complexity of the model.

Another relevant assumption done in this project is that all participants are willing to commit to the scope of the cooperation agreement. This consideration is not redundant as each player must take into consideration that, based on the results, it might be necessary to alter the internal strategies on resource deployment. For the scope of this project, every player involved is considered to be fully participatory and willing to commit to the outcomes of the analysis.

2.5.1. Legal and economical aspect

Cooperation agreement require a precise and univocal economical and legal definition. These aspect of the collaboration is partially disregarded for thesis project as these topics fall outside the area of competences of the author. Nonetheless, the literature is reviewed to ensure that the selected setting for the simulation is realistic ensuring that only plausible actions are undertaken.

[25] presents the different types of cooperation agreement formally recognised in the aviation sector. The first is the Full Alliance (FA); this type of cooperation architecture is generally set up for revenue sharing purposes, the second is Joint Venture (JV); this type of cooperation architecture is generally set up for cost sharing purposes, lastly the Merger solution is presented when the two entities formally become one.

The authors of [25] continue by stating the airlines in the same alliance "usually cooperate in various dimensions to exploit revenue synergies such as code-sharing agreements, mutual recognition of frequent flyer programs, and a number of facilities so as to provide a seamless service to interline passengers". It is also stated that these type of cooperation between airlines could also grant them deeper antitrust immunity by competition authorities.

Regarding the opportunities withing a JV agreement, the authors mention the possibility by contracting members to jointly purchase fuel, ground handling, catering, and other supplies. The JV members can also make a joint use of marketing and global distribution systems.

An analysis of the effects of these strategies applied fairly on different players can be found in [76] and [77]. The article emphasises equitable distribution and cooperative efforts among airline alliances to secure profits through sustainable collaboration, acknowledging the need to consider specific alliance types and competition dynamics, while advocating for a mutually beneficial approach that supports global sustainability and societal development.

2.5.2. Code-share

As mentioned, one of the most influential strategies to exploit revenue sharing is code sharing. This technique consists of the possibility for "one carrier to market under its two-letter designator code a certain number of seats on a flight operated by a different carrier", as explained by [25]. This specific technique well suits the scope of the project as it allows to share part of the network between collaborating airlines.

Code-share agreements already represents more than 6% of major airlines revenues ([29]). In [81] is shown that a "positive relationship between the number of code-sharing partners and an airline's operating margin". The authors also point out that the benefit is more commonly seen in revenue gains rather than reducing cost impacts.

Code-share agreements also entails some risks for the airlines. In [29] it is stated that code-share is highly affected by revenue management and pricing steps and that the airlines in the agreement either jointly exploit the customers' willingness to pay or they will inevitably cannibalise between each other. The code-share is currently tackled as a tactical step and thus its effects on the network definition are limited. A graphical representation of the typical airline code-share revenue management process can be found in [30] and [31]; which well captures the cyclical approach to code-share that re-runs part of the strategical steps after the process has been optimised.

This project aims at analysing the possibility of implementing the code-share steps earlier on in the airline planning process to allow a maximisation of the environmental benefit that can be obtained by using this technique. Shifting this evaluation to the side of the network planning will also potentially allow the airlines in the agreement to obtain a fairer distribution of revenues ([76]). A similar approach has been proposed in [41].

2.6. Solving techniques

The solution techniques can be divided in two main categories. The first being for the optimisation sections; these strategies usually concern the operation research optimisation and algorithms to improve the efficiency of the optimisation processes, the second category relates to simulation strategies for the collaboration between collaborating entities.

2.6.1. Operation Research

Traditionally, to solve complex and extremely large problems as the ones in the airline organisation process, solvers are employed. For this project a commercial solver (Gurobi) will be employed. This solver provides an efficient environment for Linear Programming (LP). Gurobi has a native implementation of Branch and Bound algorithm (B&B) and allows for the combination with other algorithms and heuristics to reach the solution effectively as desired.

The problem found in the literature can generally be solved through the implementation of LP and for the tasks analysed in this project the final strategies revolved around either Mixed Integer LP (MILP) or even Integer LP (ILP). An example of B&B being applied on a LP program can be seen in [36] where the fleet and flight planning problem are tackled. Other early applications of LP to solve the FAM can be found in [1] and [4].

The applicability of this approach can also be seen in more recent publications such as [58]. In [79] it is possible to see a complete literature review of the solution methodologies used in other relevant publications to solve the FAM.

As stated, it is possible to combine the native B&B with other algorithms or even impose different solution heuristics and bypass the need for B&B. In the comprehensive literature review just cited ([79]) another recurrent solution strategy can be identified: Column Generation (CG). This algorithm, allows to significantly cut processing times in larger problems; the CG is largely employed in the literature as shown in the aforementioned table and in [41].

This project is likely to include a variety of solution strategies as it aims at solving more than a single problem and it is foreseen that the differences of each problem will require dedicated solution strategies depending on the size of the problem that is going to be generated. Based on the literature, it is expected that a large employment of B&B will be necessary for smaller tasks while for challenges such as FAM the solution will be sought after using CG.

2.6.2. Collaboration simulation

As stated in Section 2.5, the cooperation between the two organisation is expected to be delegated to a third non participating party. This architecture is set up to partially capture the complexity of data sharing in the aviation sector. With this partial elimination of the uncertainty and subjectivity from data, strategies that aims at including these characteristics in their models such as Fuzzy Set are not going to be considered. It is important to note that two sources has been found that includes this extra layer of complexity in their model ([64] and [24]).

The simulation of collaboration is often implemented in the literature through an Agent Based Model

(ABM). In [42] a detailed analysis of all the characteristics of ABM are presented. The author introduces the Contract Net Protocol (CNP) as the main technique for collaboration and cooperation in a ABM architecture. It is stated that CNP well suits tasks of resource allocation such as the one of interest for this project. The advantages of using a CNP are various, for this project it is interesting to have dynamic task allocation, natural load balancing and failure recovery. A complete graphical representation of the CNP architecture can be seen on page 12 in [42].

To find Pareto solutions to resource allocation tasks, agent acting in the ABM often require the possibility to apply additional strategies. In the literature examples have been retrieved of possible strategies that could be employed to reach a solution. In [50] it is possible to find a detailed literature review of most common methods. One of them is Cooperative or Non-Cooperative Game Theory (GT). This method can be seen applied in large variety of studies and for different goals. Some publication relevant for the scope of this study are [15], [76], [25], and [57].

Other tools given to agents to perform their duty found in [50] are Nucleolus and Bid-Price. It is to be noted that the application of one does not necessarily exclude the others and it is not uncommon to find multiple tools being combined. While the literature on cooperation for aviation that covers the use of Nucleolus is limited, many researches use Bid-Price strategies to solve resource allocation problem related to the aviation sector. [68] shows the application of Bid-Strategies combined with GT to improve Air Traffic Management. In [42] an extensive and precise description of the different bidding strategies are presented. The author also states that bidding mechanism well match a price-incentive based model as the one proposed in this project.

The straightforwardness of bidding mechanisms and the availability in the literature of existing architectures make Bid-Price strategies the selected tool to integrate the CNP to be used in this project to effectively allocate resources between participating airlines.

2.7. Summary

With the advent of computers for commercial use the aviation sector saw an opportunity to step up its operation organisation and planning. To provide a comprehensive overview of the work published over the years, while limiting the number of articles to the most potentially pertinent ones, it has been decided to adopt a backward snowballing technique starting from comprehensive existing literature reviews.

This literature study focuses on the Strategic and Tactical phases of the airline planning process as those are the steps that are going to be included in the thesis project.

The strategic phase consists of tasks with a time horizon that spans from long to very long. Some decision to be taken in this strategical part can also be prior to the establishment of the airline; such as Hub location and service type selection and fleet composition. However for the scope of the project, the spotlight is given to the demand forecast and the network planning, considering the scenario of existing airlines.

To forecast the passengers demand several strategies were reviewed. It was concluded that, in accordance with the established trend in the field, a gravity model is to be used to estimate the passenger demand between locations. It was further concluded that, to capture the variability of the demand, it is necessary to include the possibility for the decision taken by the airline to affect the results obtained from this initial forecasting action.

The network development model to be selected is then expected to possess such capability to capture effects of decision on passengers demand. An example of suitable model can be found in [10].

The Tactical phase also includes several steps. For the scope of this project only the schedule development is analysed. Having a full schedule allows to quantify properly the expected emissions and thus climate impact.

To reach the creation of the schedule it is first necessary to model the network that the airline is going to operate. Using the outcomes of the network planning section it the necessary to create a network capable of supporting the fleet assignment phase. In the literature, two strategies have been reviewed to accomplish this goal. The first is trough a connection network and the second is with a Time and Space Network. Based on the consideration found in the literature the time and space network is deemed more suitable for the scope of this project as it appeared that it efficiency when using large networks surpasses the one of connection network.

This chapter also includes the literature review on how the collaboration between to organisation as the airlines can be implemented. After having established the set up of a model that uses fully open and accessible information (White scenario), the different solution being used by airlines to cooperate with other airlines have been reviewed.

The aim of the review of legal and economical aspects of the collaboration agreements is mainly to anchor the project in the custom of the sector rather than expanding the knowledge on these topics. It has been seen that airlines collaborates formally trough alliances and joint ventures to respectively share revenues and costs. A normal practice to share revenues is to set up code-share agreement that allow airline to market seats on flights operated by partners. The practice of code-share has been demonstrated to have a positive impact on the airline's revenues. Code-share is currently considered in between the strategical and tactical phases, but it has been shown evidence of previous attempt to apply this paradigm also in earlier stages of the airline planning process, as it is interest for this project.

Finally, the literature covering solution techniques has been analysed. The use of Linear Programming is fundamental to solve any of the challenges identified and, in accordance with most common practices found in the literature, the project will set up to use Branch and Bound and Column Generation. The techniques identified to structure the collaboration between airlines were various; after an analysis of the retrieved literature it has been concluded that this project will make use of an Agent-Based Model that also exploits Bid-Prices strategies to successfully allocate resources among participants.

3

Environmental impact

This chapter aims at presenting to the reader the literature available on the subject of environmental impact in relation with the scope of the thesis project.

In Section 3.1, the reader is presented with the context of environmental impact and which aspects of this wide field are of interest for this research. This section also includes the methodology followed to select the relevant documents. In Section 3.2 the different climate metrics used in the literature are presented and compared while providing insights on the advantages and shortcomings of each one. In Section 3.3 are presented the different methodologies used in the literature to convert emitted quantities to environmental impact. This entails a detailed analysis of the different factors that affect the conversion from quantity of chemical species to environmental impact evaluated using a metric from Section 3.2. In Section 3.4 are presented the different strategies that are currently been used to include environmental aspects in the airlines' economic balances. Lastly, in Section 3.5 are presented the most common simulation environments used to achieve the different aspects previously introduced. The chapter is finalised with a short summary, in Section 3.6, of the most relevant considerations presented in the previous sections.

3.1. Context

The relevance of aviation environmental impact has grown over the last decades alongside with the widespread concern for the critical global environment conditions. The increased interest in the topic can also be seen from the substantial number of studies and related publications released in the last twenty years. To gather relevant and up to date information on the topic, the following query was employed.

"Airline" AND (("Environment" OR "Environmental Impact") AND ("En-route" OR "Single Flight") AND ("Emission" OR "Air quality") AND (Non CO2 effects OR GWP) AND (Altitude OR Climate sensitivity))

The search was performed on Google Scholar and Scopus by looking at documents published in the last decade (after 2013). The process resulted in 74 documents of potential interest. Each of them was reviewed. The search was then expanded by using a backward and forward looking snowball method.

The result of this search highlighted the presence of three research groups that lead the way in the research of this field. These are Deutsches Zentrum für Luft- und Raumfahrt (Germany), Technische Universitat Dresden (Germany) and Delft University of Technology (The Netherland).

The aerospace sector contributes in different ways to the global environmental impact. Substantial emission sources can be identified in the aircraft production process (from the material extraction to their processing), the supply chain of the aviation market, the landside and airside handling in airports, and the airborne emissions generated by burning aviation fuel.

For the scope of this research, the focus will be restricted to the climate impact related to the flight phase of aviation. Analysing the direct and indirect effects of aviation emissions is the core focus of the project. To compare the effectiveness of any proposed solution it is crucial to identify a quantification method. Furthermore, to base decision on single flights it is in the interest of this project to define a flight-specific numerical representation of the impact generated. Having an en-route & flight-specific formulation is a straightforward approach to operate strategic network planning decisions.

In this evaluation it emerged the importance of correlating emissions to impact trough mathematical model. By considering different chemical species and their effects it is possible to obtain a significantly more refined evaluation. In order to effectively include the effects from different chemical species it is important to consider factors that affect such emissions, such as speed, engine type, aircraft type and impact of external conditions.

3.2. Climate metrics

The choice of a specific climate metric significantly affects the end result; its characteristics must thus undergo a proper evaluation. [59] underlined the importance of properly choosing a metric over another while stating that no broad consensus has yet been reached among the scientific community to which is the optimal metric. The reason behind this is likely that every metric is developed to answer specific questions and not for a general use. Each of these metrics are based on simplifications, approximations and are often based on extrapolation from, sometimes limited, big-data databases analysis; this is necessary for the development of a working and applicable model.

3.2.1. Emitted quantities

[32], in their comparison of different metrics, presents an early approach to the problem that simply relied on the emitted mass of an individual species. This approach presents several shortcoming; as the authors recognise, this type of information can provide only insights on the relative importance of different sources but it lacks the ability to compare different species. This metric does not provide any information on climate impacts.

3.2.2. Radiative Forcing (RF)

A first attempt to bridge this gap between emitted quantities and climatic impact was done with the introduction of the Radiative Forcing (RF) metric. As described by [59], RF "measures for the perturbation of the Earth's natural radiative equilibrium due to the cumulative effect of a (mostly) anthropogenic change of the atmospheric composition relative to the pre-industrial state".

This metric allows for a first comparison between the effects of different species and it was seen that a linear relationship exists, under the assumption of a constant RF over time, with the temperature change that follows a perturbation. Its straightforward approach made this metric popular and widely used as can be seen in [40] (in its RFI variation) for informing flight choices among conflicting emissions estimates, in [38], for the definition of eco-labels for general aviation aircraft, and in [63] which makes use of the effective RF.

However, the RF metric has some relevant limitations. The main issues with RF are thoroughly described in [28]. In first instance, RF is an instantaneous and backward-looking metric, thus non suitable for forecasting or future-looking evaluations. The authors continue by highlighting that RF neglects any consideration of the timescale of the global mean surface temperature response associated with gradual thermal absorption by wide bodies of water, "thereby disregarding any lasting impact of short-lived climate forcing species". RF was proven as a poor evaluation metric for representing the relative significance of short- and long-lived climate forcing species. [35] further observed that the introduction of certain simplifications in the RF calculation of short-lived species and methane significantly affected the evaluation of the overall impact of oxides of nitrogen (NO_x), resulting in an underestimate of its global impact.

3.2.3. Global Warming Potential (GWP)

To obtain a more accurate understanding of the total lifetime impacts of the factors considered a time integration was introduced. This led to the creation of a new metric: the global Warming Potential (GWP). This metric which consist of an integration over time of the RF resulting from a single pulse emissions. GWP represents well the effect generated by long-lived species and allows for the different forcing species to be weighted against one another. This characteristic of the GWP makes it possible to ascertain the equivalence of different species ([28]).

Despite some limitation the GWP is widely used also in policy-making and academic. It has also been used in some of the most authoritarian bodies such as the Intergovernmental Panel on Climate Change (IPCC). In addition, GWP was also used in the Kyoto Protocol and the United Nations framework Convention on Climate Change([28]). Other relevant documents in which GWP has been chosen as the evaluation metric are [80] and [56] both interested in the trajectory optimisation of a given flight.

Regardless of its widespread usage, GWP is connoted by some limitations. As the metric integrates over a longer time span, it sometimes falls short in the correct representation of temperature changes at a given time. It is possible to have two different species, one greatly affecting the short period and the other with a lower impact but more sustained in time, resulting in similar GWP estimates. Making it more challenging to determine the impact of each species at a specific point in time ([28]).

3.2.4. Global Temperature Change Potential (GTP)

An attempt to obtain a more precise metric over time was done with the creation of the Global Temperature Change Potential (GTP). This metric shows the surface temperature change at a given time resulting either from a pulse or a sustained emission. This is done by selecting an adjustable time horizon and using the temperature change obtained in the last year of such defined horizon; making the GTP an endpoint metric ([28]).

3.2.5. Average Temperature Rise (ATR)

The last metric analysed in the literature is the Average temperature Rise (ATR). ATR accounts for the lifetime of the different species, the different climate sensitivities and the thermal inertia of the atmosphere-ocean system ([18]). This metric is usually considered with one of 20, 50 and 100 years as its time horizon; this depending on the scope of the evaluations.

ATR is selected by several research groups for its ability to, similarly to the previous two metrics, capture the spatial impact of the emissions but also the climate relevance of the emitted species while providing a snapshot of the resulting scenario. Some examples of its usage in the literature are: [59], [34],[67], [75], [14], and [20].

3.2.6. Metric choice

Following the process proposed by [32], it is possible to identify among the above mentioned metrics which best fits the scope of the project. As the environmental evaluation to be performed is a future forecast of the effects originated by different emitted species from a single flight, it is reasonable that metrics such as Emitted Quantities and RF are disregarded. As the inability of Emitted Quantities to capture the climate impact generated and of RF to provide reliable future looking forecasts mine the intent of the evaluation.

Among the remaining metrics the literature converged to the usage of ATR, and more specifically ATR20 (20-years horizon), to represent the short-term climate impact of en-route emissions. The considerations which led researcher, such as the previously cited ones in "Average Temperature Rise", where dictated by the need to optimise the 4D trajectory of a flight; such evaluation dose not distance itself much from what is required for this project. The characteristics in the climatic interests that pool these literature publications from this thesis's goal point at a justified decision in selecting ATR as the climate metric of reference.

3.3. From Emissions to Impact

Following the choice of the proper climate metric it is crucial to define a method to compare the climate effect of different chemical compounds and, more broadly, of aviation's impact on atmospheric environment. Since the climate impact of aviation is influenced not only by CO_2 but also by other fuel components and atmospheric chemistry, studies like [8], that solely focus on reducing CO_2 emissions, fall outside the scope of this study.

3.3.1. Constant conversion

The first approach found in the literature is to multiply the emitted quantities of each species times a compound specific emission conversion constant. This very intuitive method utterly disregards atmospheric chemistry and is based on the assumption that outsides condition at the moment and following the emissions do not have a considerable impact on the final climatic effect that each different species has on the environment. This approximate conversion strategy has the benefit of requiring very little computation and also allows for considering emission patterns uniquely based on fuel burnt. CO_2 is used as reference and every species has an Equivalent CO_2 constant that should represent how much an emission quantity of 1 kg impacts the environment compared to 1 kg of CO_2.

[43] provides an example of possible application of this method. The authors investigate the optimisation strategies in flight detours to avoid high charging air spaces and trace the emission back to fuel burnt per distance travelled. This basic approach is sometimes also employed in the policy making as described in

[49]. Another example of this method being employed can be seen in [39]. In this paper, the authors make an attempt at refining the conversion accuracy by differentiating the fuel usage rate in different flight phases.

The assumption on which this method is applied are too broad and do not allow for an accurate evaluation of external factors. One of the most recurrent indirect emission impact considered in the literature is contrail formation; contrails impact are ignored by the constant conversions method. This phenomenon is object of interest as its effects greatly depend on the external conditions at the moment of emission including the time of the day, the humidity, the temperature and location ([27], [53], [44], and [54]). Taking in consideration the considerable limitations of the constant conversion method it is possible to conclude that this approach is unsuitable for the scope of this project.

3.3.2. Climate Change Functions (CCF)

The first conversion method was based on the constant conversion and entailed a mean square error (MSE) (obtained from the comparison with AirClim CO_2 equivalents data, [17]) of over 1.18. A first refinement was obtained with the introduction of the flight length method, which brought the MSE to 0.24. Later on, it was shown that even more precise results could be obtained with the consideration of additional parameters; In [18] it is presented that a simple addition of latitudinal dependency as additional factor resulted in a further improvement of the MSE (decreased to 0.19).

With the intent of developing an even more accurate conversion strategy, the research group working for the "Institut fur Physik der Atmosphare" developed a new strategy to convert the emission to climate impact ([33]). This new approach is defined as Climate Change Functions and makes use of the ATR climate metric calculated individually for every species to account the overall climate impact. These function where defined for the project REACT4C founded by the European Commission. In [46] it is stated that for their development "eight different North Atlantic weather patterns have been developed based on detailed simulations with atmospheric chemistry models". The authors further explain that these function measure the impact of every relevant species emitted alongside with the contrail formation as a function of the location and time of emission. The model can also include the atmospheric chemistry with direct aerosol effects, indirect Green House Gas (GHG) emissions and contrail and aviation induced cloudiness ([62]).

In [18], the authors state that the climate impact shows a significant dependence on altitude and geographic region. The only species that does not present such behaviour is CO_2 due to its long atmospheric lifetime, for all the others it is necessary to define a more accurate model to account for external conditions and variations.

These high-fidelity functions however suffer from a high complexity in terms of computational requirements and thus limit their direct applicability ([20]). Furthermore, the CCFs calculation is based on specific weather patterns in the North Atlantic region; this limits their applicability for a more generic scenario.

3.3.3. Algorithmic Climate Change Functions (aCCF)

To counter the substantial computational requirements of using CCFs and to expand their applicability to a wider reange of scenarios, [67] researched an algorithmic approach capable of providing qualitatively similar results as CCFs while limiting the computational power needed. The authors state that the functions obtained well approximate the effect of all the most relevant species in the Northern extra-tropic area. Using the CCFs as comparison the authors also tested the fidelity of aCCFs for each species. The results underlined the reliability of such functions and that the impact originated from water vapour is simulated with the highest accuracy while the model present a lower accuracy in evaluating the impact that NO_x emissions have on the ozone.

The parameters used for the definition of aCCFs are latitude, longitude, altitude, temperature and time; these affect the solar flux, the geopotential and the potential vorticity which are considered in the evaluation.

The marked practicality of aCCFs leads to the swift adoption of these functions for most investigations on flight-specific climate impact. Examples of their adoption in the literature are: [75], [14], [46] and [20]. It is also relevant to note that a new publication, [78], by the same research group is, as of the beginning of 2023, being revised; this publication deals, similarly to the scope of this project, with the implementation of aCCFs to evaluate en-route emissions.

3.4. Economical evaluation of Emissions

For the prosecution of the project it is necessary to define a numerical value that conveys the total climate impact generated by a specific operation, in this case a flight. Quantifying with a value the climate impact allows airlines to internalise in their decision process this effect of their operations. This could be used to implement new strategies committed to reducing the environmental impact that current aviation has. In the literature are analysed several solution techniques used in reality to shift the aviation's effect to a quantifiable economical entity. It is an established and proven concept that having quantifiable market-based measures based on marginal cost pricing can lead to significant benefits for the environment ([59] and [48]).

3.4.1. Command and Control

One of the most straight forward approach is to define a "command-and-control" approach where, after having set precise and univocal thresholds, a penalty is applied to those who trespass such limitation.

The definition of the aforementioned thresholds is often an outcome of political discussion and thus challenging to separate from political opinions. While it is reasonable to state that a reduction in today's volume of aviation's traffic entails a significant benefit for the environment, it is not to state that a "degrowth" of the sector is the only applicable solution as it is done in [65]. Reducing the aviation sector as the only solutions for the environment not only denigrates the substantial efforts and resources devoted to improving such sector, but also overlooks the social effects of shrinking an entire economical segment.

Imposing limits to the annual emission quantities allowed for specific forcing chemical species is one of the countermeasures taken, alongside others, to contain the environmental impact of the aviation sector. Having clear and specific limitation is fundamental to restrain the annual emissions of aviation. Considering that the scope of the project is to improve and make more efficient the current usage of resources this limitations does not capture well this goal but can later be adopted to expand its outcomes.

This approach is often paired with, and implemented through, the creation of additional environmental taxes that are to be met by the operators when surpassing predefined annual emission quantities.

3.4.2. Trading scheme

Another method used to contain the climate impact of aviation is Trading Schemes. This approach consists of trading off emissions allowances for aviation's climate relevant species. In order to make this conversion possible it necessary to have in place a conversion methodology between different chemical species and then between a species of reference (usually CO_2) that can be converted into an monetary value.

This system has been adopted by the European Union (EU). Since 2012, the EU has fully integrated international aviation. The operators, regardless of their origin, are obliged to surrender allowances for CO_2 emissions when flying over Europe ([59]). This trading scheme adopted by the EU takes the name of European Trading Scheme or ETS in short.

The most significant limitations of this method are in first place that, nowadays, the precise quantification of the climate impact is overlooked in favour of a partial fuel-usage metric that approximates the actual impact of aviation to only its emissions of CO_2. Secondly, the price of an emitted tons of CO_2, used as conversion reference to transform the climate impact to monetary value is highly fluctuating. This metric greatly affects the final operational costs for airlines; its inconsistency can pose a significant treat at long term planning by the airlines. Examples of the high variability in the cost of one ton of emitted CO_2 can be found in the literature such as in [80] where the cost is set to 35 and in [56] where it is set to 65.

Regardless of its limitations, the adoption of this approach well suits the scope of this project that aims to induce the airlines to internalise, partially or totally, the climate cost of their operations. It is in the scope of this study to overcome the first limitation previously presented. The ETS method, flanked with the species comparison described in Section 3.3, allows for the complete inclusion of different chemical species and atmospheric-chemistry phenomenons in the airline's operational cost of each flight.

In [59] are analysed the long-term effect of applying trading scheme on the environment as well as a combination between this approach and a NO_x emission airline charge. The result of the paper shows that "a global trading scheme for the political regulation of both CO_2 and non-CO_2 emissions of aviation [...] would be the best solution from an economic and environmental point of view". Furthermore, the authors conclude that to obtain positive environmental outcomes it is also necessary to set up the possibility to purchase CO_2 permits from stationary sources.

3.5. Simulation environments

During the review of the literature it was possible to ascertain that a variety of different simulation tools have been used to simulate and compute various aspects of the climate impact of flights.

As the scope of this project of defining and quantifying the emissions generated by a single flight largely overlaps with the goal of defining the emissions obtained by operating different paths and trajectories, typical of in the trajectory optimisation research, a significant majority of the literature reviewed for the environmental section of this document consists of publications and researches related to the trajectory optimisation topic.

3.5.1. TOMATO

One of the most used simulation environment is TOMATO. This modular simulation software is an air traffic simulation environment based on accurate trajectory optimisation which includes the estimation of engine emissions while providing both trajectories and Air Traffic Flow Management assessment. TOMATO has been developed to bridge the gap between multi-criteria optimum flight paths and Air Traffic Management constraints.

TOMATO, or "TOolchain for Multi-criteria Aircraft Trajectory Optimisation", is capable of processing a wide variety of data as input. These include 4D weather data, Aircraft specifics (family, type, engine, weights, ...), airspace information (charges and restrictions), airline goals (cost objectives and strategies).

With the proper definitions of Key Performance Indicators (KPIs), TOMATO optimises and returns the 4D trajectory (time, latitude, longitude), fuel consumption, emissions and demand on Airspace capacity ([54]).

This overarching software despite its modular architecture works as a closed box, where input data are processed and only final results are returned to the user. The complexity of each module makes it challenging to grasp and limits the implementation of any variation by a non so accustomed user. Moreover, the combination of trajectory optimisation and Air Traffic Management requires a substantial computational power. TOMATO well suits the scope of 4D trajectory optimisation but might result overachieving for smaller scopes such as the one of this project that takes the trajectory as fixed and non object of further optimisation.

In the literature it can be seen a consistent employment of this simulation software specifically by the research group of the Technische Universistat Dresden, yet its adoption is rarely seen from other research groups. This might be due to the previous consideration; the resources needed to get accustomed to such a complex and overarching tool are substantial, making the selection of TOMATO a choice to be taken only when the needs of the research align with what can be obtained from the software.

Some examples of its usage by the Technische Universistat Dresden's group can be found in [43], [26], [56], [53], [44], [55] and [54].

3.5.2. TOM

TOM is a Trajectory Optimisation Module. This computational tool uses optimal control techniques in order to determine climate optimised aircraft trajectories. More practically, this approach aims at minimising an environmental cost function while satisfying dynamic constrains and state control and path limitations ([48]).

This more simple approach to trajectory optimisation allowed several researchers to integrate relevant aspect of the evaluation to meet their requirements. An example of this can be seen in [48], where TOM is combined with CCFs (previously presented in Section 3.3). The same combination was re-used by the authors in [49]. It is noticeable to state that the just cited research group also developed the CCFs and aCCFs; however, even if the second publication happened in 2021, after the definition of aCCFs already presented in 2019 ([67]), the authors decided not to use the new algorithmic approach in the trajectory optimisation module. The combination between TOM and aCCFs however can be found in [75] and [46].

This module also was deemed adequate to evaluate the local effect of aviation on Air Quality and Noise ([47]).

In contrary with the limitations of TOMATO presented in the previous subsection, TOM consists of a much more straightforward and more malleable tool. However, it appears clearly that its reason of being, as stated by the name itself, relay mainly in trajectory optimisation. This difference in the final scope, when compared with this project, lead to partially discard the selection of TOM as a suitable simulation tool.

3.5.3. OpenAVEM

The last relevant simulation environment reviewed in this section of the literature review is OpenAVEM. This simulation tool differs from the others as it is not in its objective to optimise the trajectory of flights but rather to deepen the level of detail on the emissions of each flight.

This tool uses a bottom-up approach to account for total emissions. The choice of such approach allows to obtain precise environmental evaluation as a sum of the emission from each flight. To refine further the emission patterns, OpenAVEM uses Automatic Dependent Surveillance - Broadcast (ADS-B) data to tack the real trajectory followed by each flight ([51]).

The possibility to evaluate arbitrary flight paths using ADS-B derived flight performances models sets OpenAVEM apart from the other simulation tools previously considered. In the publication related to the first presentation of this tool ([51]) it is recognised that previous attempt to create a simulation environment based on a bottom-up approach have been previously carried out; however these relied mainly on the implementation of total flight distance or only on origin-destinations pairs.

The software is open access and, as TOM, its architecture is straightforward and it is overtly built as a simulation tool to obtain an emissions 3D grid for specific periods of time. In [51], the performances of OpenAVEM are proof checked by performing an analysis of the environmental impact generated by the global civil aviation and results from the literature based on fuel consumption (taking into account differences due to non considered such as military fuel etc). This analysis is performed using data from different sources to further test the adaptability of the model showing that ADS-B data from both commercial and non commercial services can be used in the simulation.

The accessibility of OpenAVEM makes it possible to adapt the software to specific needs. For the scope of this project, the results provided by OpenAVEM represent an optimal starting point that can be later paired with climate change functions to capture the climate impact of the so defined emissions.

3.6. Summary

For this section of the literature study, the review focused on scientific publications that could provide a answer to the research questions of the thesis project.

To obtain a clear picture of the state of the art of the scientific research being carried out on the environmental impact generated by flights a research query was used on major search engines for academic databases. The results were limited to the last ten years. Starting from the so retrieved 74 documents, the collection was then expanded by using a partial backward and forward snowballing method.

With a first analysis it was possible to identify three main research groups consistently contributing to the topic (Deutsches Zentrum für Luft- und Raumfahrt, Technische Universitat Dresden and Delft University of Technology).

One of the initial research question that has been investigated is regarding the selection of a proper climate metric to capture the climate impact of different types of emissions and atmospheric chemistry phenomenon. The analysed metrics are Emitted Quantities, RF, GWP, GTP and ATR. By analysing the characteristics of each metric it was possible to discard the Emitted Quantities and RF. Among the remaining ones ATR was selected a proper climate metric. The methodology of this project was anchored to common practice in the field by selecting the approach that has been predominantly used in the literature.

Then, it has been analysed what are the most appropriate strategies to convert the emissions of different forcing chemical species to climate impact. On the topic, it has been possible to notice an evolutionary trend in the literature; researchers progressively proposed more refined ways to quantify the effects of emissions. Two types of refinement steps where identified. The first step consisted of migrating from a conversion based uniquely on constant values to a more precise evaluation which also included external factors. The second step was directed mainly at making the obtainment of such information in a more efficient way while also expanding its applicability. The conversion method selected for this project was reasonably selected from the newest and more refined approach.

Once that the climate impact of different species is analysed it is in the interest of this project to define a structured strategy to convert this information to a numerical monetary value to be used by airlines to better include the environmental aspect during their decision processes. The literature was reviewed to answer such question.

Two general approaches were identified; the first, "Command and control", is characterised by the imposition of taxes, penalties and other economic measures to limit the quantity of emissions. Even if this first approach is fundamental for a successful implementation of environmental measures, it is often based on emitted quantities and not on climate impact. While it is not neglected that the implementation of such approach combined with a climate impact evaluation could produce substantial benefits for the environment, it is interest of this study to focus on the efficiency of employed resources and not on the total emitted quantities; a limitation of this approach is that it values relative improvement over absolute improvement.

The second approach is trading schemes that allow airlines and operators to purchase allowances for a certain emitted quantity. This well covers the intent of the project as it allows for an economical conversion of previously computed climate impacts.

Lastly, it was necessary to answer to the research question of which simulation environment should be used. This review is fundamental to ensure that the project is based on up-to-date methodologies and to avoid the recreation of existing software. With the review, it has been possible to identify three main simulation environment, these being TOMATO, TOM and OpenAVEM. The choice ultimately fell on the third option since it is the only simulation tool specifically designed to provide 3D grid data of emissions per flight trajectory, making OpenAVEM the sole analysed alternative capable of offering a more precise evaluation of various conditions during emission. This capability is considered crucial to provide a broader range of choices for the optimisation model, core of this project. In contrast, TOM and TOMATO primarily focus on trajectory optimisation, which falls outside the scope of this study.

4

Thesis research

In this chapter the thesis research for which this document serves as literature study is summarised. The knowledge of the research project is crucial to interpret the information discussed in this document.

4.1. Research Objective

The research of this project is to contribute to the development of new environmental strategies for the airline planning process by introducing:

(a) New collaborations strategies to allow code-share like agreements in earlier stages of the planning process while expanding airline's options;

(b) Flight specific (based on average flight paths, trajectories and meteorological conditions) environmentally-weighted costs to incentives airlines to adopt more sustainable solutions and to assess the airline performances, environmentally wise, in different proposed scenarios.

4.2. Scientific Gap

Throughout this document some of the gaps in the current knowledge of the airline planning strategies and climate impact analysis of flights have been highlighted. In this section a brief summary is provided.

The project will make use of existing strategical and tactical approaches to implement cooperation. From the literature it emerged that several researches have and are being carried out to increase the efficiency of the airline operations by integrating different tasks together. The separation in tasks primarily exists for the complexity of solving the entire problem in one sitting; the separation also allows for different goals to be considered over time in the same process.

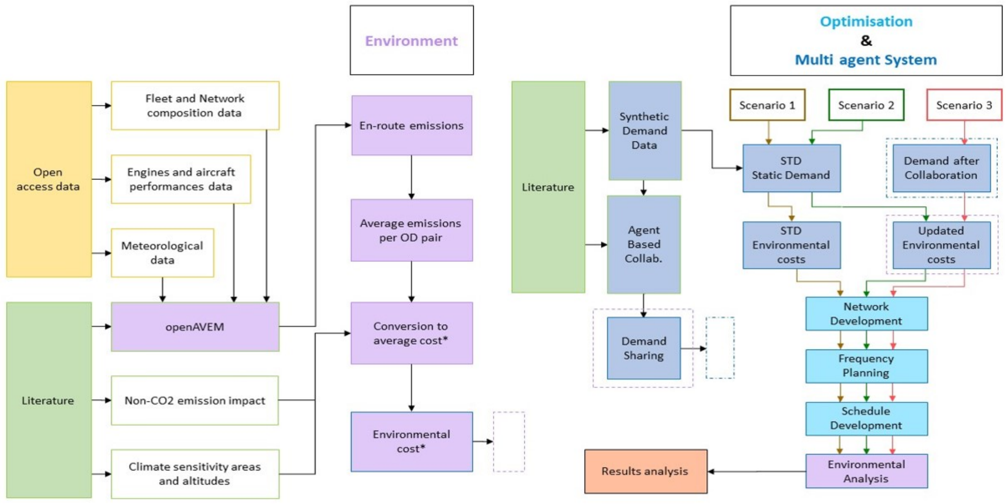
The literature, however, has not yet explored fully the potential of sharing resources between competitors. Currently, the main collaboration stages are processed repeatedly at a mid-short time horizon from the day of operation. It is the interest of this project to analyse the potential effects of introducing an additional collaboration phase in an earlier phase, a mid-long time horizon, of the operation planning. This novel phase could allow airline to attain a deeper level of cooperation and thus an improved efficiency in the resource management.

In this project, the effects produced by this additional cooperative step are going to be evaluated from a climate impact point of view. The project aims at internalising actual environmental-related cost to better capture the impact that airlines flight operations have on the environment.

The literature presents extensive research on the exact computation of emitted quantities by single flights, however this knowledge is mainly used to develop trajectory optimisation tools. This project's scope is to apply this knowledge on impacts evaluation to provide quantitative information to airline allowing them to move towards a more environmentally-thoughtful approach to operations.

4.3. Methodology

A graphical representation of the foreseen methodology that will be followed is shown in Figure 4.1.



* These data are to be evaluated per Origin and Destination pair and per each combination available in the airline's fleet of Aircraft and engine types.

Figure 4.1: Graphical representation of Project Methodology.

The methodology is hereby included only as reference of what the general structure of the project is expected to look like; the detailed description of actually covered steps will be later included in the thesis report. The project includes the following main steps:

- Literature study (presented in this document)
- Development of cooperative model
- Development of environmental model
- Synthetic demand data generation
- Model validation
- Final assessment

The prospected disposition of the given steps over the project timeline can be seen in Figure 4.2 and Figure 4.3.

4.4. Research Question

- Can the collaboration between airlines affect the impact on the atmospheric environment?
  - How can the Demand Forecast be modelled?
    - How can the level of detail be balanced by the complexity of the model?
    - Is it possible to combine the demand forecast with the network development?
  - To obtain flight schedule, what type of network should be defined?
    - What algorithms and solving techniques should be employed to accomplish the schedule generation task?
  - What level of cooperation can be considered?
    - How should the cooperation be structured? How can the research be anchored in the custom practise of the industry?
    - To what type of information from the competitor/collaborator do the airlines have access to?
    - What method should be employed to simulate the cooperation?
    - What type of resource allocation strategy should be followed?
  - Which type of metric can successfully capture the environmental impact of flight emissions?
    - How can the emissions be calculated for each flight/route?

        - How is it possible to obtain environmental impact values for each flight / route while accounting for different emissions conditions (altitude / engine setting / climatological sensitive areas/)? Is it possible to obtain these information?
            - Which emission parameters should be considered to obtain an all encompassing value?
    - What are the available strategies to convert emissions into a numerical monetary value?
    - What is the best simulation environment to obtain all the necessary information?

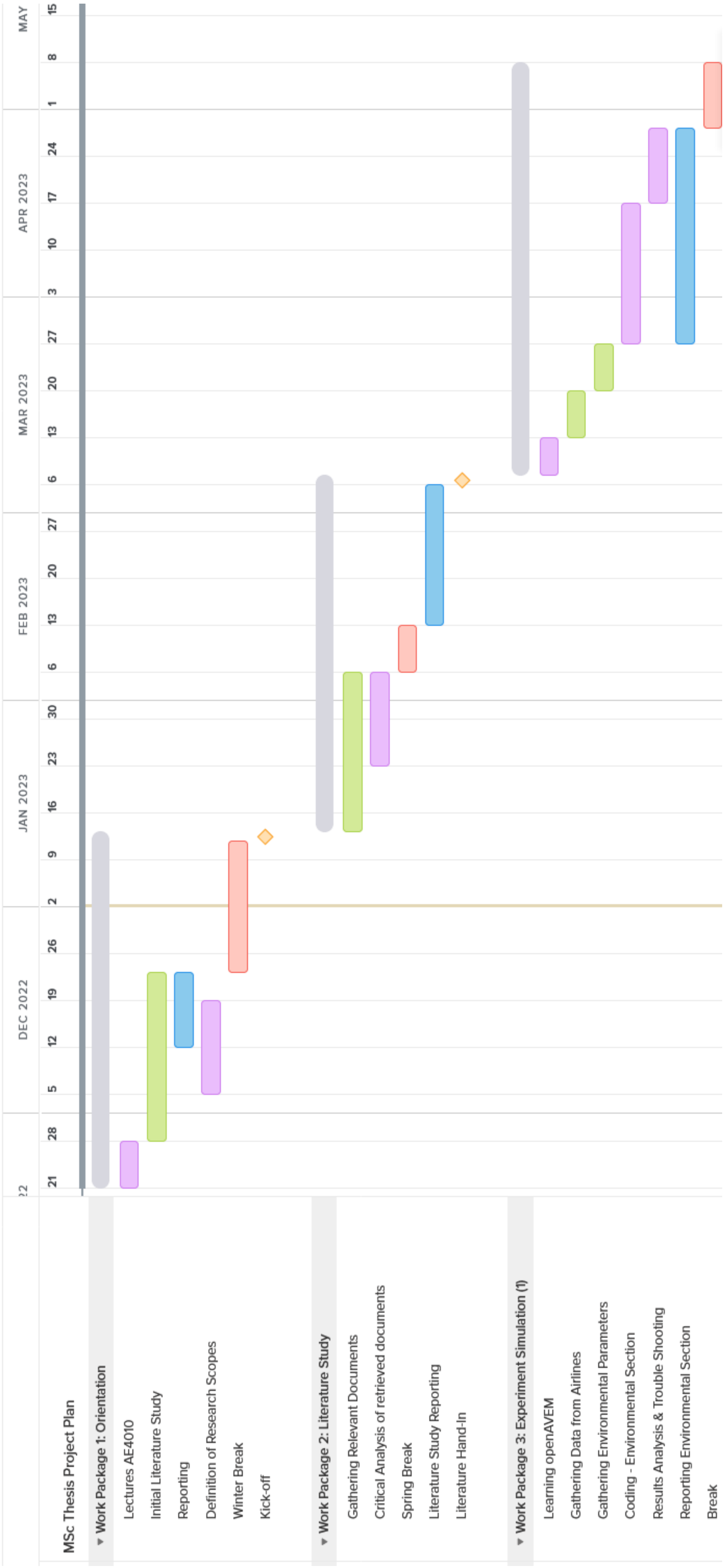


Figure 4.2: Thesis Project GANTT(1).

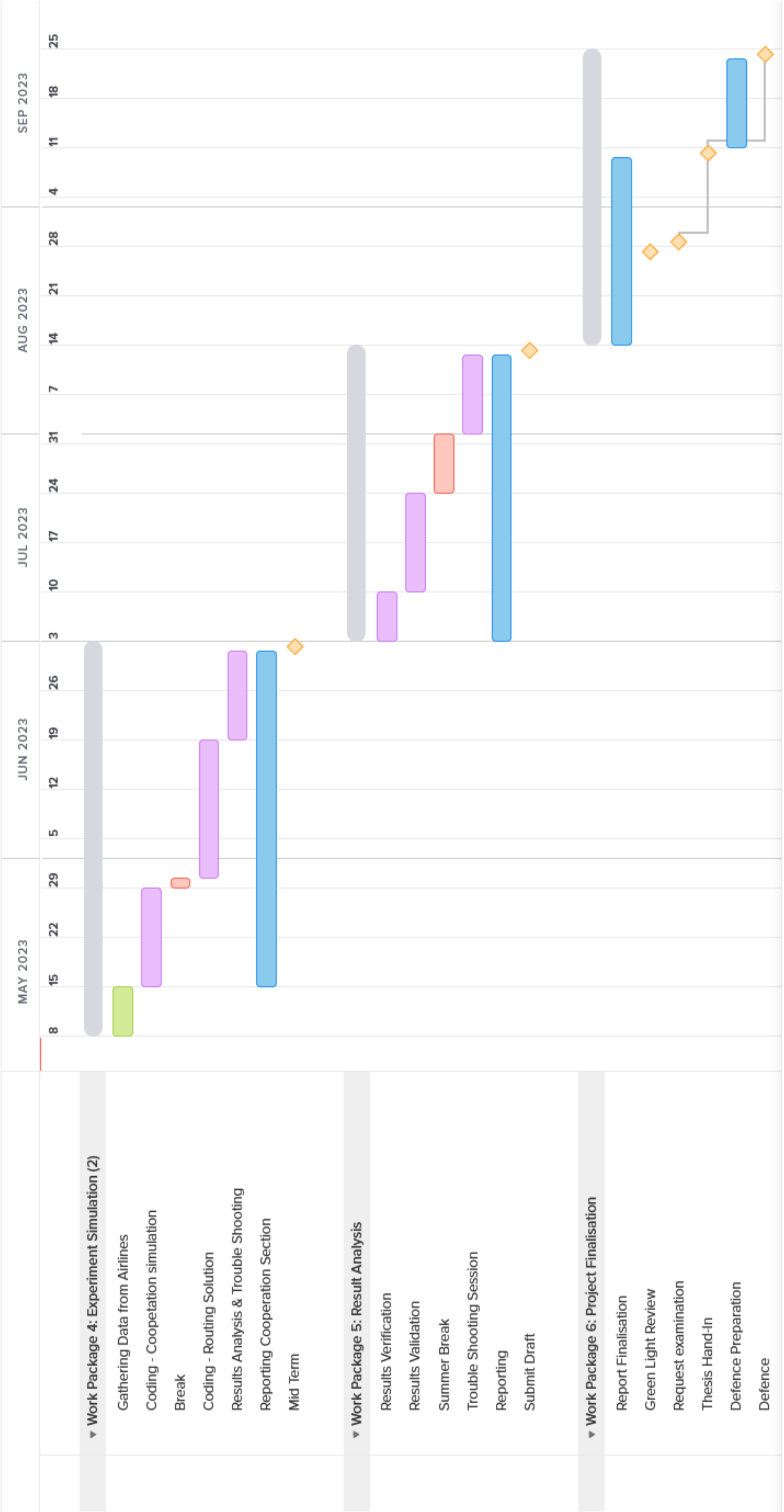


Figure 4.3: Thesis Project GANTT(2).

III

Supporting work

1

Supporting work

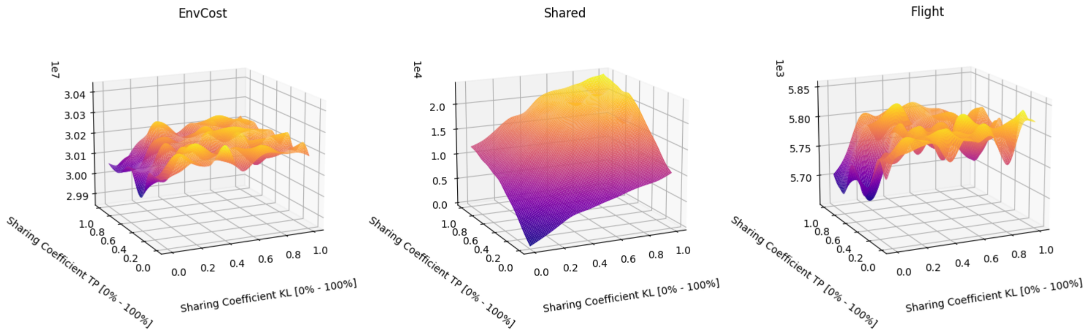
1.1. Model verification

The results of the model described in the Scientific Paper, Chapter I, have undergone rigorous testing to ensure that none of the constraints set within the model have been violated. The verification process includes several checks to maintain the integrity of the model's outcomes.

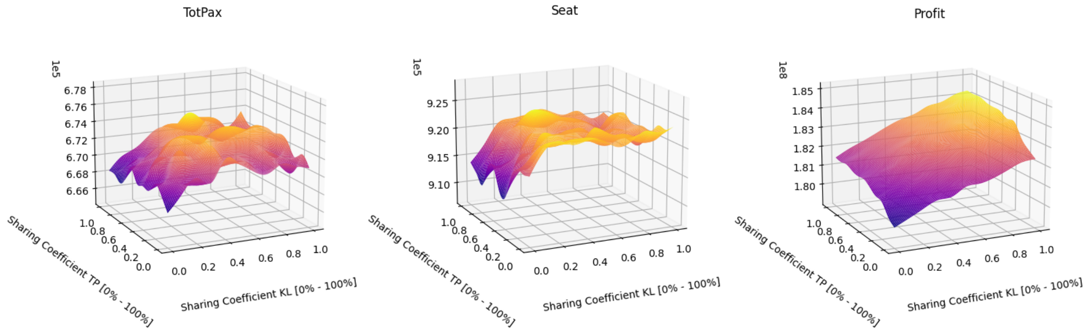
Firstly, a crucial verification ensures that no flight segment operates with a passenger count exceeding 90% of the available seats, taking into account the specific load factor, for any aircraft type assigned to that particular segment within the airline's fleet. Secondly, an extensive examination ensures that each destination reached by the airline falls within its potential network. The airline's potential network is defined as the list of locations for which comprehensive demand data are available. Lastly, a verification procedure confirms that each aircraft type is utilised within its specified availability times. The availability times are determined by a block time of 10 hours per day, calculated over a seven-day week, and multiplied by the number of aircraft of that specific type in the airline's fleet. The aircraft utilisation time for each type is derived from the summation of all flight times conducted by that aircraft type. It is noteworthy that none of the constraints were violated during the extensive verification process. Consequently, it is justifiable to consider the model as successfully verified.

1.2. First phase optimisation

To complete the results presented in the Scientific Paper shown in Chapter I are hereby included the full set of 3D graphs generated after the first optimisation phase with different ETPs.

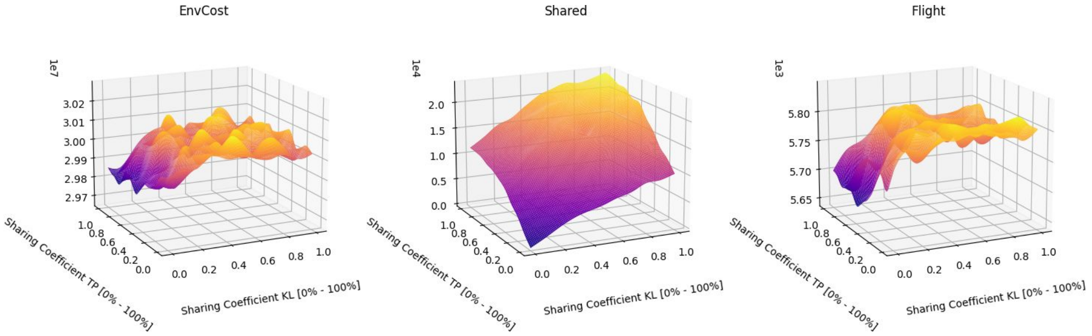


(a) Environmental Costs (b) Passengers shared (c) Flights

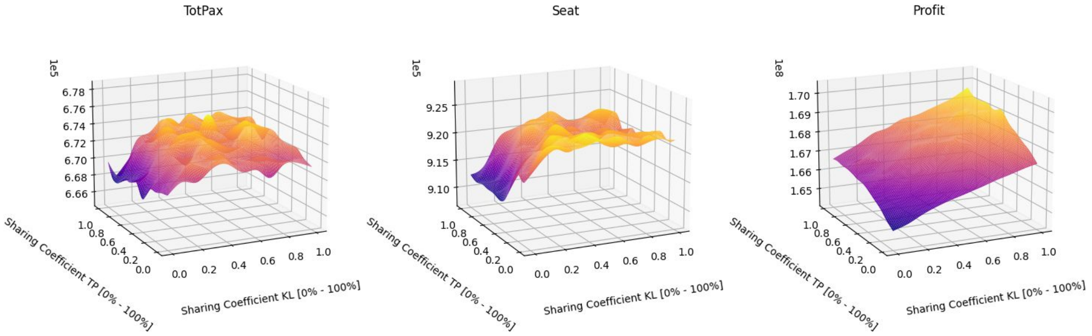


(d) Total passengers (e) Seat Capacity (f) Profit

Figure 1.1: 3D Plots of some of the obtained airlines combined results for ETP 0%.

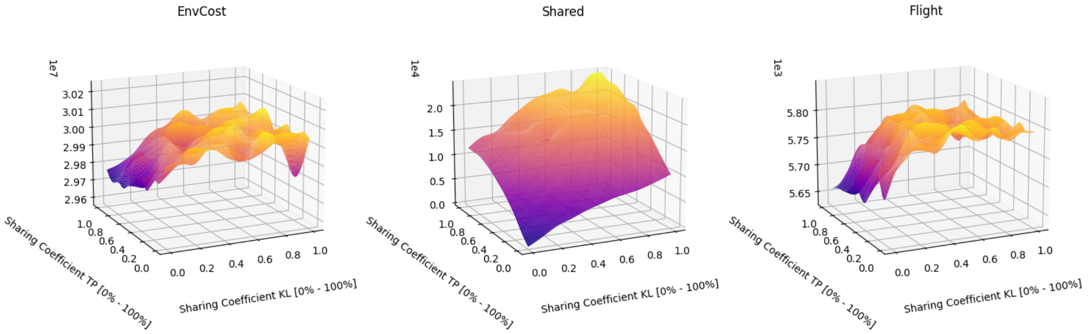


(a) Environmental Costs (b) Passengers shared (c) Flights

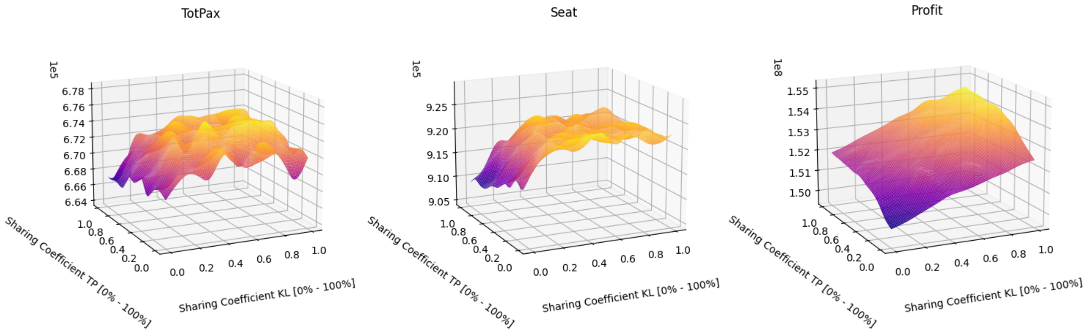


(d) Total passengers (e) Seat Capacity (f) Profit

Figure 1.2: 3D Plots of some of the obtained airlines combined results for ETP 50%.

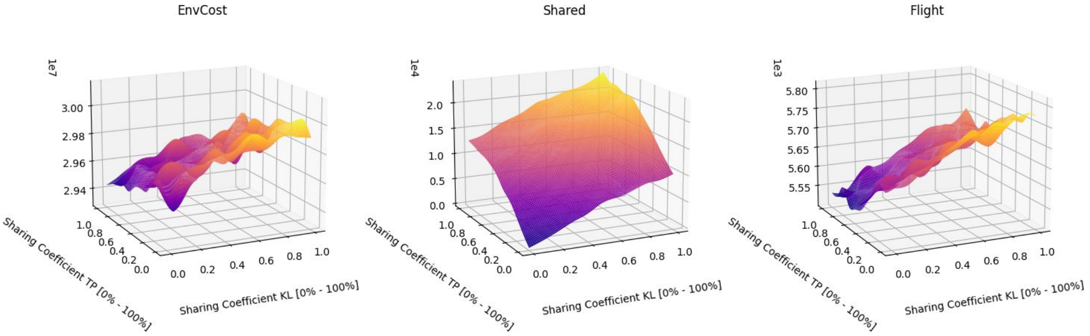


(a) Environmental Costs (b) Passengers shared (c) Flights

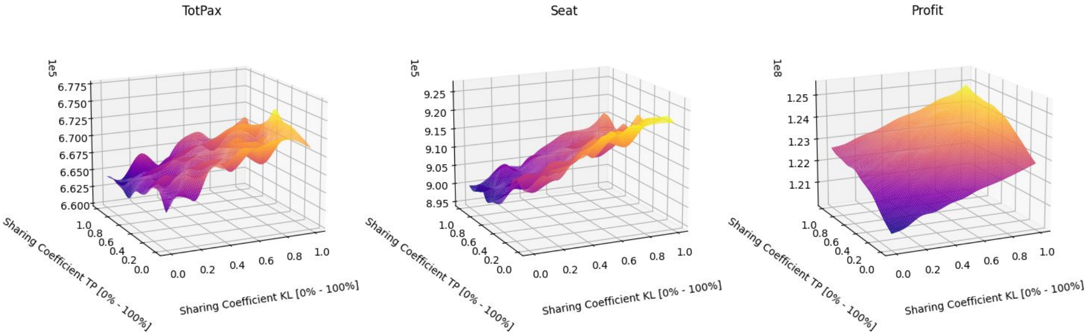


(d) Total passengers (e) Seat Capacity (f) Profit

Figure 1.3: 3D Plots of some of the obtained airlines combined results for ETP 100%.



(a) Environmental Costs (b) Passengers shared (c) Flights

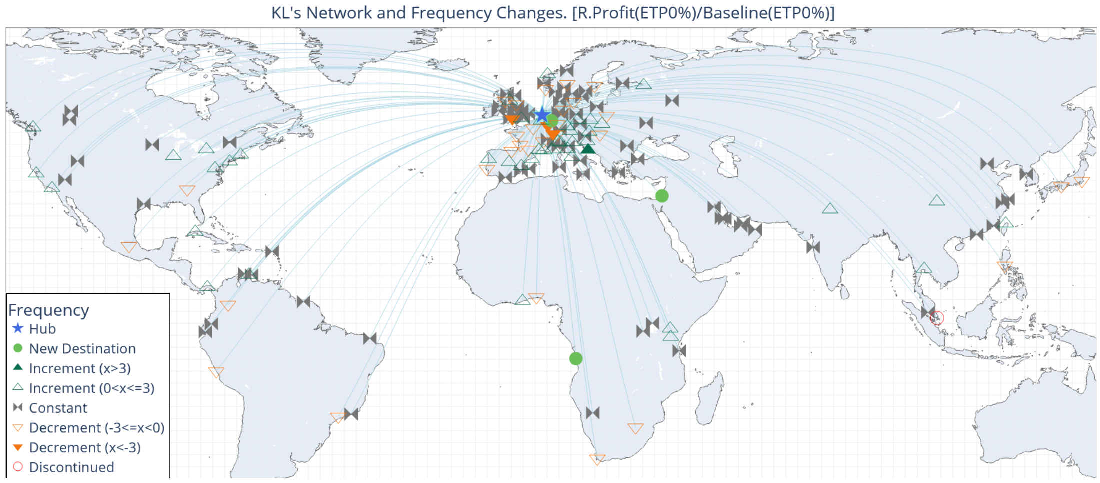


(d) Total passengers (e) Seat Capacity (f) Profit

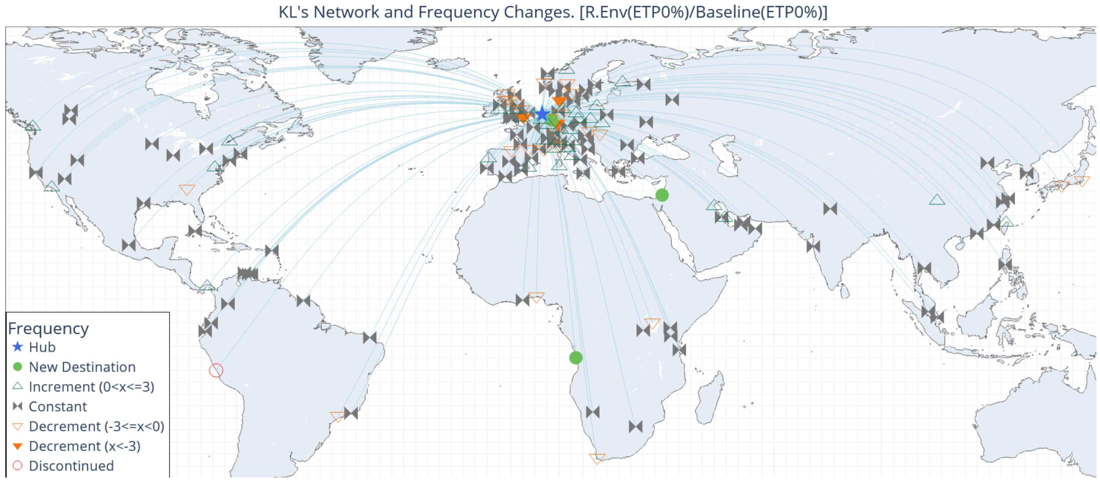
Figure 1.4: 3D Plots of some of the obtained airlines combined results for ETP 200%.

1.3. Frequency changes in considered scenario

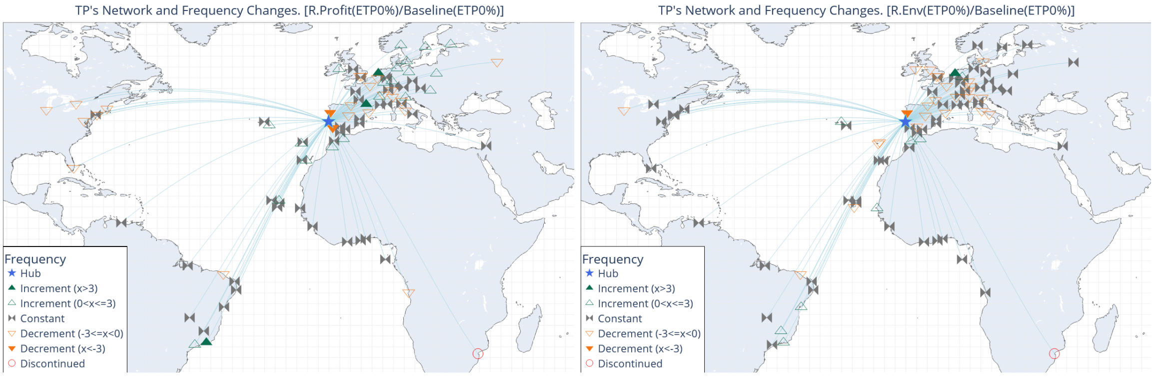
In this section of the supporting work are presented the graphical representations of the frequency changes in both airlines' networks compared to the "Baseline" scenario. In these geographical maps it is possible to witness the variation of flight frequencies by also highlighting more significant changes; the threshold to define a more relevant change is set to three flight difference.


KL's Network and Frequency Changes. [R.Profit(ETP0%)/Baseline(ETP0%)]

(a) KL R.Profit.

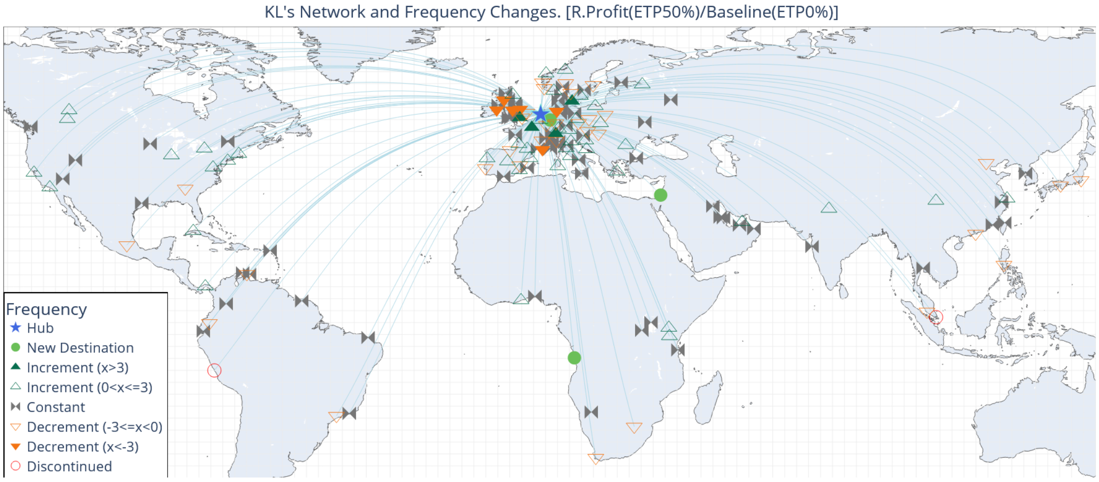

KL's Network and Frequency Changes. [R.Env(ETP0%)/Baseline(ETP0%)]

(b) KL R.Env.


TP's Network and Frequency Changes. [R.Profit(ETP0%)/Baseline(ETP0%)]
TP's Network and Frequency Changes. [R.Env(ETP0%)/Baseline(ETP0%)]

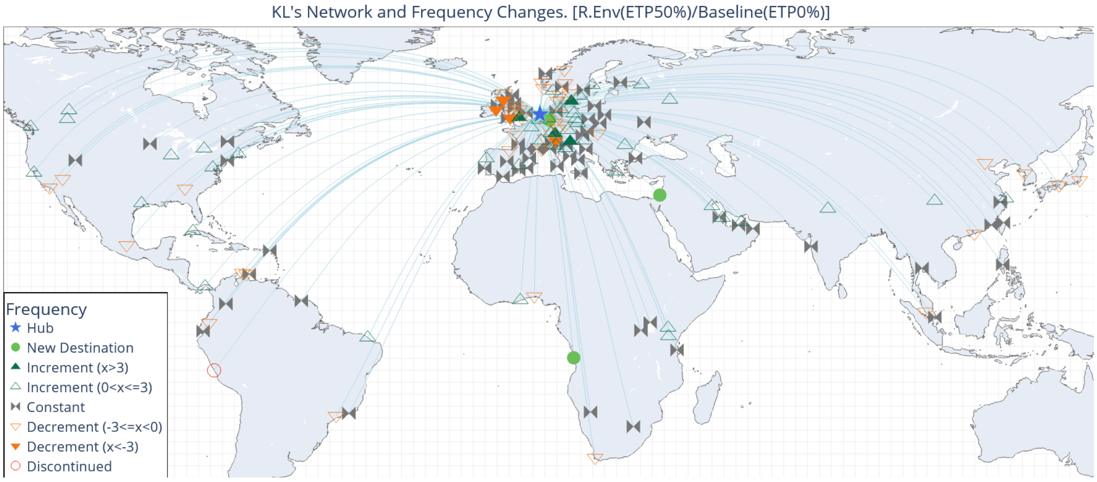
(c) TP R.Profit.
(d) TP R.Env.

Figure 1.5: Frequency changes for ETP 0%.



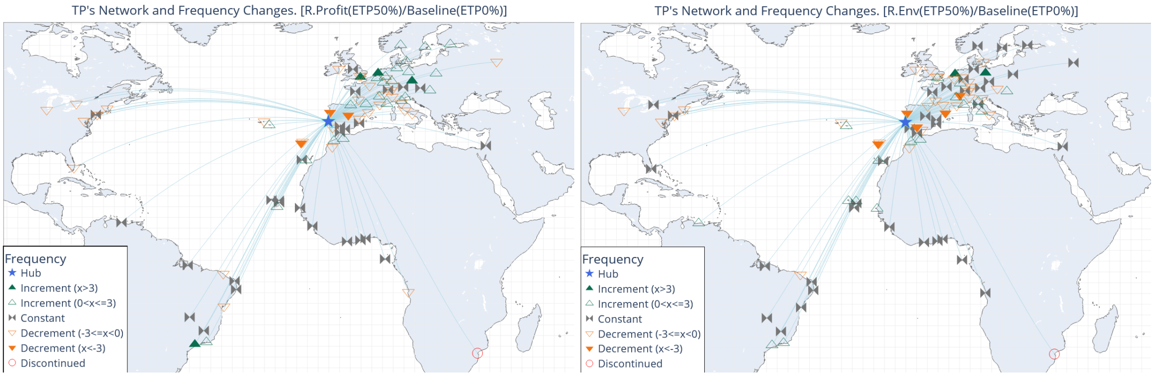
KL's Network and Frequency Changes. [R.Profit(ETP50%)/Baseline(ETP0%)]

(a) KL R.Profit.



KL's Network and Frequency Changes. [R.Env(ETP50%)/Baseline(ETP0%)]

(b) KL R.Env.



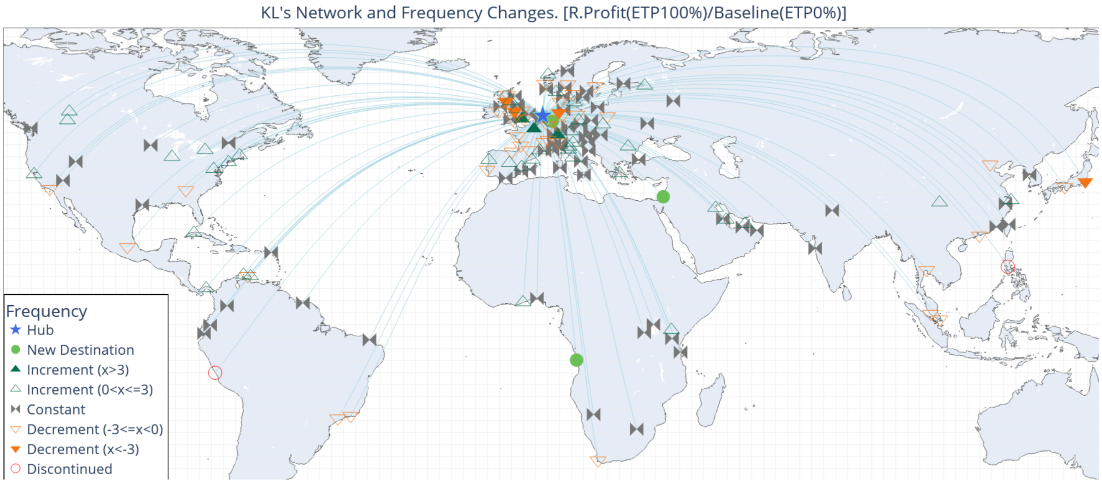
TP's Network and Frequency Changes. [R.Profit(ETP50%)/Baseline(ETP0%)]

TP's Network and Frequency Changes. [R.Env(ETP50%)/Baseline(ETP0%)]

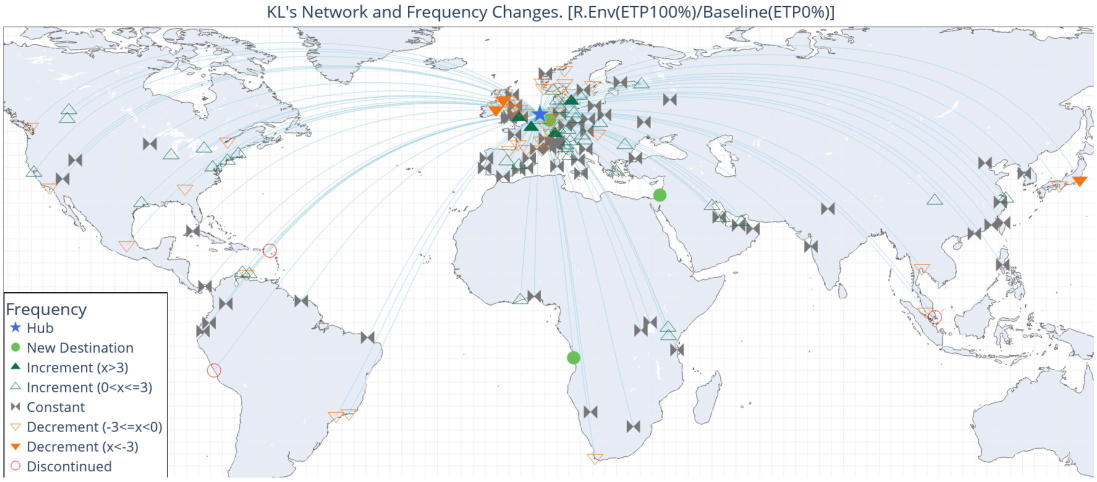
(c) TP R.Profit.

(d) TP R.Env.

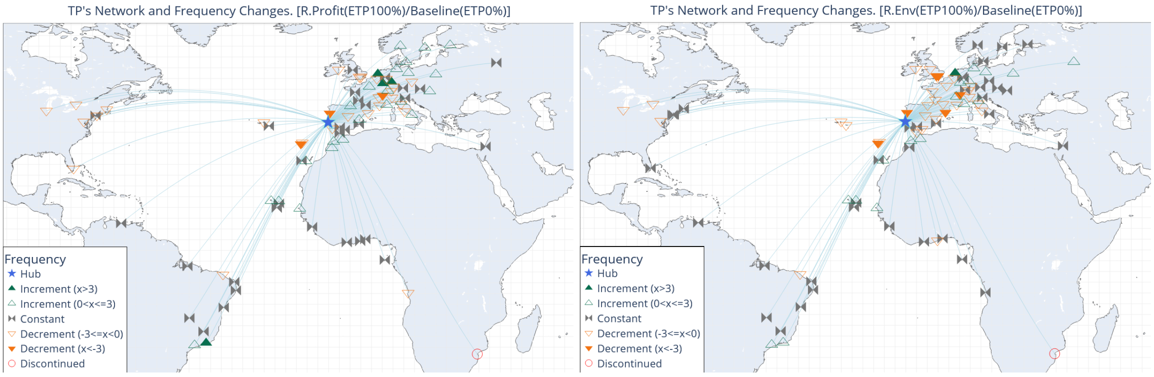
Figure 1.6: Frequency changes for ETP 50%.


KL's Network and Frequency Changes. [R.Profit(ETP100%)/Baseline(ETP0%)]

(a) KL R.Profit.


KL's Network and Frequency Changes. [R.Env(ETP100%)/Baseline(ETP0%)]

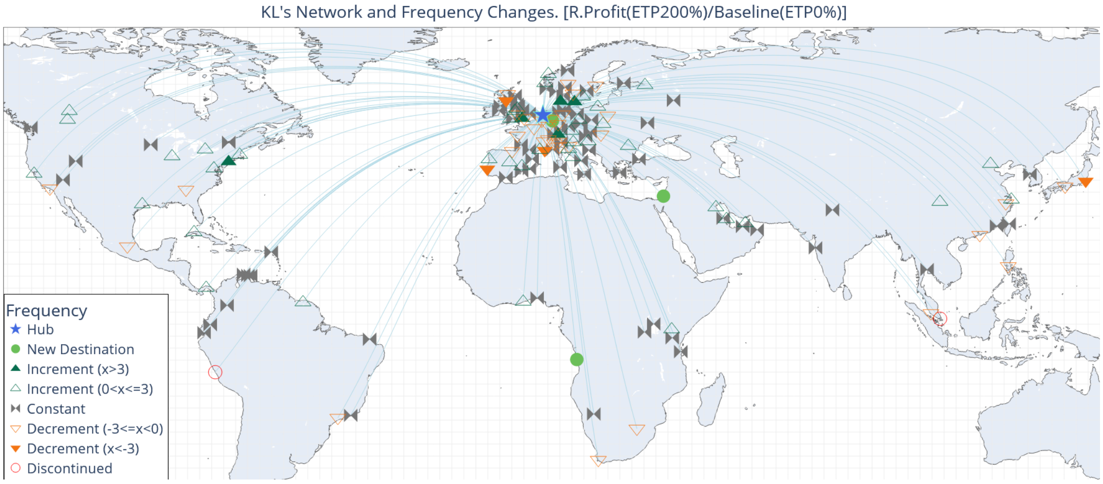
(b) KL R.Env.


TP's Network and Frequency Changes. [R.Profit(ETP100%)/Baseline(ETP0%)]
TP's Network and Frequency Changes. [R.Env(ETP100%)/Baseline(ETP0%)]

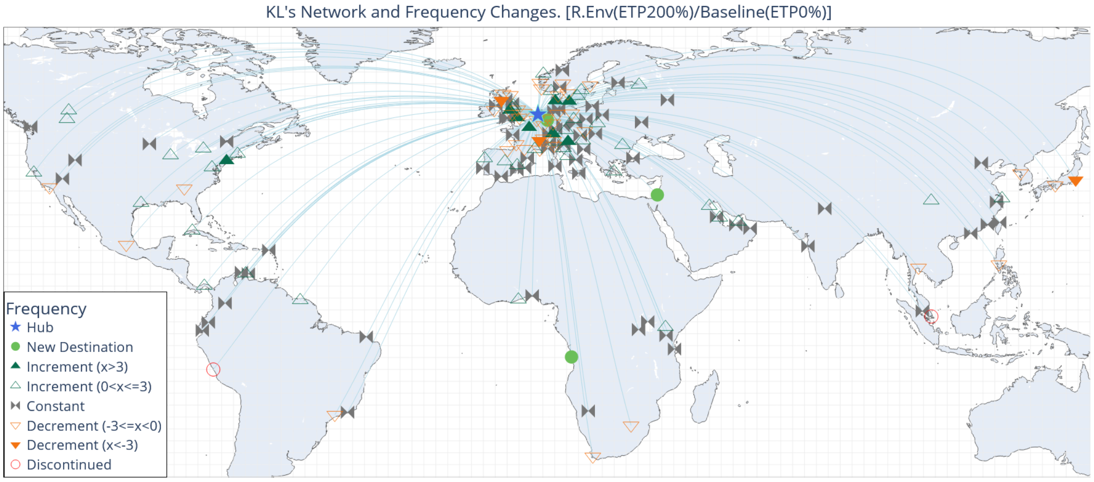
(c) TP R.Profit.

(d) TP R.Env.

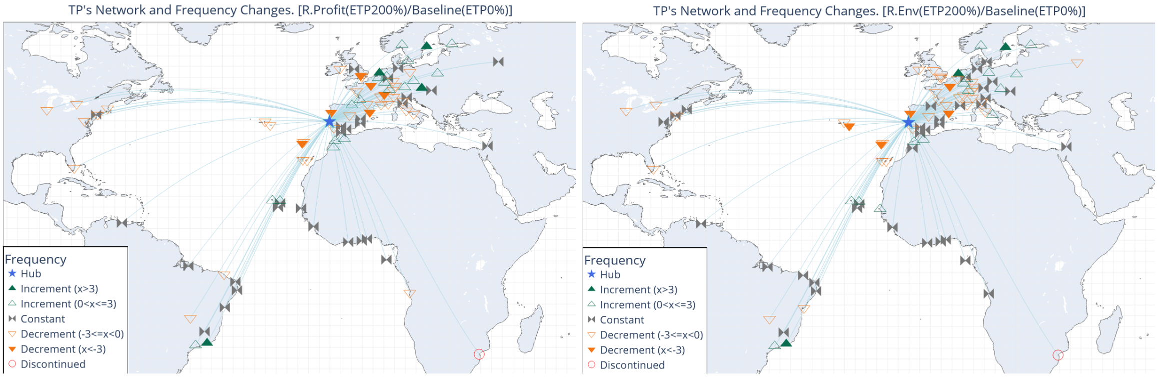
Figure 1.7: Frequency changes for ETP 100%.



(a) KL R.Profit.



(b) KL R.Env.



(c) TP R.Profit.

(d) TP R.Env.

Figure 1.8: Frequency changes for ETP 200%.

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