

Towards Sustainable and Passenger-Centric Airline Networks

An Optimization Approach to
Airline Network Design with Climate Impact &
Passenger Preferences

MSc Thesis
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by

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Preface

Dear reader,

This master's thesis marks the culmination of my academic journey at TU Delft, bringing my student life to a close. It has been an intense yet incredibly rewarding experience, and I am deeply grateful to those who have supported me throughout this process.

First and foremost, I would like to express my heartfelt gratitude to my first supervisor, Petra Heijnen. Your unwavering support, guidance, and dedication have been invaluable. Our weekly meetings were not just a routine but a source of inspiration and motivation. Together, we developed the model that forms the backbone of this research, and your expertise and encouragement have made this accomplishment possible. I cannot thank you enough for your patience and commitment to this project.

I would also like to thank my second supervisor, Jan Anne Annema, for the valuable insights you provided throughout this research. Your focus on refining the outcomes and pushing me to think critically about the implications of my work significantly shaped the final results. Your feedback challenged me to improve and brought clarity and depth to my analysis.

I am also thankful to my parents for their unwavering support throughout my studies in the Netherlands. Their encouragement has been a steady source of motivation. I would like to extend my gratitude to my friends for their support during this time, with special thanks to my best friends since high school, Irmak, Cavdar, and Ayca, who have always been there for me.

With this thesis, I close the chapter of my student life at TU Delft, carrying with me the knowledge, experiences, and memories that have shaped who I am today. I look forward to the new opportunities ahead.

*Ekin Korkut
Delft, August 2024*

Executive Summary

The aviation industry is undergoing rapid expansion, with an annual growth rate of 4.5% to 5%, positioning it as the fastest-growing mode of transportation worldwide. This growth, however, comes with significant environmental challenges, primarily due to the industry's substantial contribution to greenhouse gas emissions. Currently, aviation accounts for 2.4% of global CO_2 emissions and 3% of the European Union's total greenhouse emissions. If current trends persist, these figures are expected to rise dramatically, intensifying the urgency for the industry to align with international climate agreements, such as the United Nations Framework Convention on Climate Change (UNFCCC), by adopting eco-conscious strategies to reduce both CO_2 and non- CO_2 emissions. One way to achieve this is by reconsidering their airline networks.

Airlines have traditionally focused on a cost-driven approach when optimizing their network structures, often sidelining environmental impacts. This approach, primarily motivated by market demand and operating costs, seeks to develop a network that minimizes expenses while maximizing profitability. However, with increasing awareness of the aviation industry's significant contribution to climate change, it has become essential to consider whether airlines can achieve both cost-efficiency and environmental sustainability through strategic changes to their network design.

As the aviation industry evolves, so do the expectations of its customers. In this service-oriented business, delivering high-quality service is a core competitive advantage. This advantage is closely linked to how well airlines listen to and act on customer feedback, particularly by integrating this to early stages of their operational decisions. Understanding passenger needs and expectations is crucial, as decisions made without considering these factors can lead to reduced customer satisfaction. For instance, optimizing a network solely based on cost and climate impact might lead to less convenient flight schedules or routes, which could alienate passengers who prioritize certain departure times or direct routes.

Given these complexities, it is clear that airline network design must go beyond just cost and environmental considerations. Integrating the passenger perspective is crucial for developing a network that meets both operational goals and customer satisfaction. This leads to the need for a more holistic modeling approach that combines three key objectives: minimizing costs, reducing environmental impact, and accommodating passenger preferences.

The proposed modeling approach in this research aims to address this challenge by developing an optimization model that integrates the economic goal of cost minimization with the environmental objective of reducing CO_2 emissions and the service-oriented goal of satisfying passenger preferences, particularly in terms of departure times.

To support the development of this comprehensive optimization model, a thorough literature review was conducted to identify the specific criteria necessary for integrating environmental considerations and passenger preferences into airline network design. This review focused on understanding the environmental impacts of aviation, particularly CO_2 emissions, and the various strategies airlines can adopt to mitigate these effects. Additionally, it explored the importance of passenger preferences, with a particular emphasis on departure times, as a critical factor that can influence network design.

Following the literature review, existing hub location models were analyzed to assess their applicability in this context. While traditional models are effective for optimizing cost-driven networks, they often fall short in addressing the additional layers of complexity introduced by environmental and passenger considerations. The research identified specific needs arising from these considerations, such as the need to account for CO_2 emissions linked to flight frequency and the importance of aligning flight schedules with passenger preferences. To address these gaps, the models were adapted and extended, incorporating these new objectives to create a more holistic approach to airline network design.

The developed model was then tested using the well-known CAB dataset, a benchmark in hub location

research. The testing phase included both single-objective optimization, where each of the three objectives (cost, environment, and passenger preferences) was optimized individually, and multi-objective optimization, where the model sought to balance all three objectives simultaneously. This approach allowed for a comprehensive evaluation of the model's effectiveness in producing network designs that meet the diverse needs of airlines in today's complex operational environment.

This research provides a significant contribution to the field of airline network design by introducing an optimization model that harmonizes the often conflicting goals of economic efficiency, environmental sustainability, and passenger satisfaction. Through an integrative approach that accounts for the complexities of modern airline operations, this study advances the understanding of how these diverse objectives can be balanced within a single framework. The proposed model, tested using an established dataset, demonstrates its potential to influence both academic discourse and practical applications by offering a more nuanced understanding of the trade-offs inherent in network design. Moreover, this work highlights the broader social and scientific relevance of incorporating environmental and passenger-centric considerations into strategic planning, urging a shift towards more sustainable and responsive practices in the aviation industry.

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Nomenclature

Abbreviations

Abbreviation	Definition
ATR	Average Temperature Response
CAB	Civil Aeronautics Board
CO_2	Carbon Dioxide
EC	European Commission
EEA	European Environment Agency
EU	European Union
H_2O	Water Vapor
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
LTO	Landing and Takeoff
MIP	Mixed-Integer Programming
NO_x	Nitrogen Oxides
O-D	Origin-Destination
OI	Operational Improvements
UCHLP	Uncapacitated Hub Location Problem
UNFCCC	United Nations Framework Convention on Climate Change

1

Introduction

1.1. Problem Introduction

With an annual growth rate of 4,5-5%, aviation has the highest growth rate among all modes of transport, making its environmental impact particularly significant [2]. In alignment with the principles set by the United Nations Framework Convention on Climate Change (UNFCCC), substantial initiatives must be undertaken to reduce both CO_2 and non- CO_2 emissions through the implementation of eco-conscious strategies and operations [3]. Every industry must take steps for the shift to sustainable operations, especially the aviation industry which is responsible for 2,4% of CO_2 emissions and 3% of the EU greenhouse emissions [4].

There has been a notable growth of greenhouse emissions from aviation, marked by an annual increase of 3,6% [5]. Should the current trend persist, projections indicate that aviation emissions in 2036 could be 155% to 300% higher than those recorded in 2006 [6]. CO_2 emissions from international aviation are anticipated to be nearly quadrupled by 2050, compared to the levels observed in 2010 [7]. The increase in greenhouse gas emissions from aviation is detrimental not only to the climate but also to public health, contributing to a higher incidence of cardiovascular diseases, neurological and respiratory disorders, cancers, and premature mortality [8].

To address the growth of aviation and its environmental impact, governments, aviation authorities, and enterprises have implemented strict environmental regulations to incentivize airlines to adopt more environmentally sustainable practices [9]. The response from the Dutch government towards this movement was to implement a cut back on aircraft movements at Schiphol from 500,000 flights per year to 452,500 flights per year to mitigate noise and CO_2 reductions [10]. Given that Schipol serves as a vital hub for many airlines, such cutbacks could significantly impact their network. The reduction in flights might lead travelers to choose less efficient routes with similar environmental consequences, thus questioning the overall environmental benefits [10]. Notably, objections to the cutback plan were voiced not only by airlines but also by governments and the European Commission, prompting a reconsideration by the Dutch government [11]. Consequently, airlines are compelled to explore alternative measures to navigate these challenges, one of them being the redesign of their network in consideration of the climate impacts.

Traditionally airlines adopted a cost-driven approach when optimizing their network structure, and climate impacts are not taken into consideration [12]. Mainly driven by market demand and operating costs, airline network optimization aims to deliver a minimum-cost plan [12]. Given the necessity to reduce the climate impact of aviation, it is worth considering whether an airline can achieve this goal through structural changes to its network.

As a service-oriented business, delivering high-quality service provides a core competitive advantage for airlines [13]. This advantage is closely linked to attentively listening to customer feedback early in the transaction process and effectively addressing their identified needs [14]. It is essential for airlines to understand their customers' needs and expectations [15]. When network decisions are made based

solely on airline costs and climate impact, passenger satisfaction might be adversely affected. Therefore, taking a step further than just considering the airline and environmental perspectives, integrating the passenger perspective into network decisions is crucial.

1.2. Airline Networks

In recent decades, most major airlines worldwide have undergone significant transformations and are operating with a hub-and-spoke network model [16]. With the 1978 Airline Deregulation Act, major airline carriers adopted a hub-and-spoke network as opposed to the common point-to-point network structure [17]. Hubs leverage economies of scale by enabling a smaller number of higher-capacity routes to efficiently serve many origin-destination pairs [18].

Prior to the deregulation in 1978, the Civil Aeronautics Board (CAB) was responsible to award airline operating certificates, allocate routes and decide on ticket prices [19]. This strict regulation on airlines limited competition and flexibility. Early airline routes, modeled after railroads, were linear and inefficient. Despite expanding geographical coverage post-World War II, connections were often poorly coordinated and inconvenient [19]. Economic challenges and the success of deregulated airlines featured the inefficiencies in the regulated system. This led to the transformation of point-to-point systems to hub-and-spoke networks after deregulation.

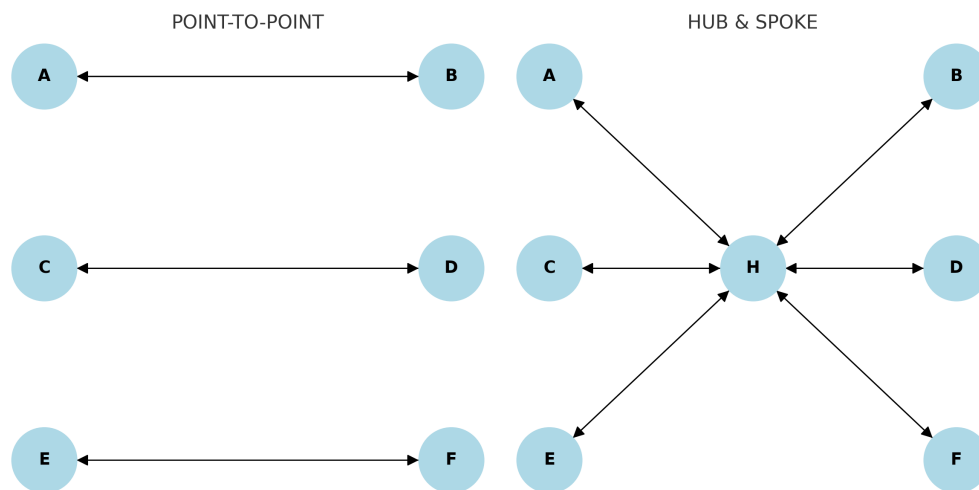


Figure 1.1: Point-to-point and Hub & Spoke Network Architecture

Figure 1.1 highlights the difference between point-to-point and hub-and-spoke network architecture. Most large airlines choose to operate as a combination of two [19]. A point-to-point system allows passengers to board at their flight origin and depart at their final destination. As opposed to this, the hub-and-spoke system only allows passengers to travel to hubs from their origin, and make an extra journey to their final destination if their start or endpoint is not the hub.

Both hub-and-spoke and point-to-point have advantages depending on the market needs of an airline. An airline operating on a wide geographic area with many destinations can benefit from a hub-and-spoke design as it allows to serve destinations with fewest routes [19]. An airline serving a market of five destinations, only require to operate four routes with one hub. In a point-to-point system, ten routes would be required to connect all destinations. The hub-and-spoke system can connect any origin-destination pair with fewer routes, and thus requires the fewest number of aircraft [20]. Many airlines are driven by the competitive advantages of expansion to larger coverage areas with a hub-and-spoke model. Expansion for an airline has many advantages, such as increased connectivity, encouraged travel and improved asset utilization [21]. As the airline network grows, expanding to more destinations, more flight frequency is required. High flight frequency can accommodate the passenger' preferences in terms of their desired itinerary times [21]. Expansion in a hub-and-spoke network can be relatively easy, as adding one city to the network would require the addition of one extra route. This increases the

utilization of existing hubs, and can provide service to cities which might have a lower demand or are further away.

Hub-and-spoke network design benefits airlines in many ways. This network design also offers potential reductions in environmental damage per seat due to the possibility of using larger aircraft [20]. Transportation of large passenger flows using a limited number of links allows the utilization of larger aircraft. On the other hand, hub-and-spoke networks increase the travel distance for passengers and can cause large amount of pollution due to this detour, double-take-off and landing. As noted by Pels [22], passengers will reach the hub airport via a short-haul flight with high environmental costs, to reach a higher capacity inter-hub link. Given these considerations, it is crucial for airlines that adopt a hub-and-spoke structure to prioritize minimizing their environmental impact. While the hub-and-spoke design offers operational efficiencies and the potential for lower per-seat emissions through the use of larger aircraft, the increased travel distances and additional take-offs and landings associated with this network can lead to significant environmental costs. Therefore, airlines must carefully assess and mitigate the ecological consequences of their network design.

1.3. Aviation Climate Impact

Future growth of the aviation industry is hindered by the growing environmental concerns of aviation [23]. The environmental impacts of aviation, especially noise pollution and greenhouse gas emissions, have gained increasing importance [8]. To address the growth of aviation, governments, aviation authorities, and industries have enforced strict environmental regulations and set ambitious targets, compelling airlines to adopt greener operations [8].

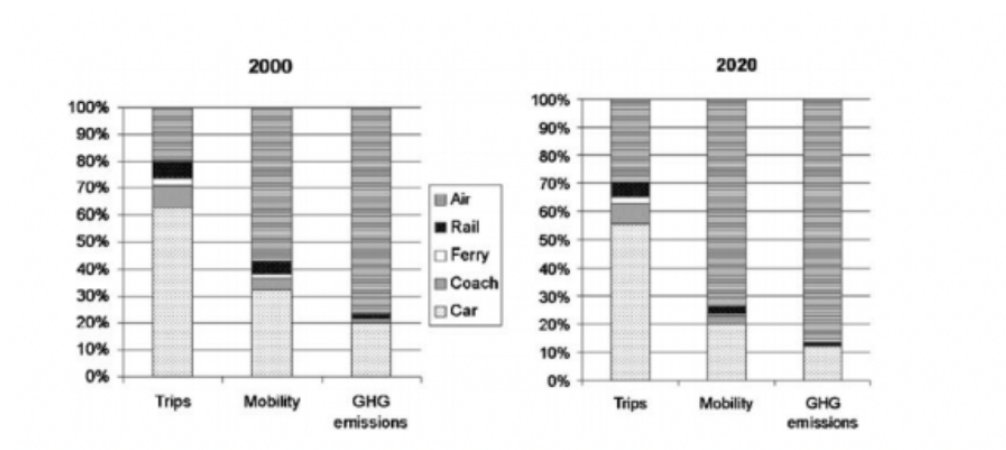


Figure 1.2: Modal split of number of trips, distances (mobility) and greenhouse gas emissions (GHG) for different modes of transport [24]

Figure 1.2 shows the modal split of number of trips, distances (mobility) and greenhouse gas emissions (GHG) for different modes of transport. As it can be seen, mobility for air transport is the maximum compared to other modes of transport. With having the lowest number of trips, air travel contributes most to the emission of greenhouse gases.

Despite progress in reducing emissions across various sectors, the rapid growth of air transportation is leading to an increase in emissions of numerous pollutants from aviation activities [24]. Additionally, noise pollution from aircraft operations is the most immediately noticeable environmental impact of aviation [8]. A robust scientific understanding of aviation's environmental impacts is crucial for informed policy decisions and the development of effective, cost-efficient mitigation measures that achieve the desired outcomes.

1.3.1. Mitigation Strategies

NLR [25] identifies three research directions that contribute to mitigating the climate impact of aviation. These research directions are:

1. Sustainable energy resources advancement
2. Novel aircraft design and aircraft performance improvements
3. Operational improvements

The first two research directions have long been studied and impacted climate research on aviation [26]. It is projected that new aircraft designs and hydrogen-powered aircraft will not be operational in the airline industry for the foreseeable future. The development and implementation of these technologies are anticipated to take at least a decade [27]. Consequently, with the urgency of mitigating the climate impact, they are not expected to contribute to the reduction of the aviation industry's environmental footprint in the short term [25].

Airlines are compelled to integrate climate impact reduction goals to their decision-making process, through improving the sustainability of their operations. This includes implementing Operational Improvements (OIs), which focus on utilizing the currently available fleet and technologies [26]. One way to achieve this is by reconsidering their airline network design.

To address these environmental concerns, optimization strategies considering climate impact can be implemented. By incorporating environmental factors into network optimization models, airlines can minimize the carbon footprint of their operations.

1.4. Importance of Passenger Preferences

In any service-oriented business, delivering high-quality service leads to a core competitive advantage [13]. High-quality service is closely linked to attentively listening to customer feedback early in the transaction process and effectively addressing their identified needs [14]. It is essential that airlines understand their customers' needs and expectations [15]. Even though airlines frequently measure their customer's perception of their services, they evidently lack a deep understanding of their customer's expectations [28]. This can significantly impact the resource allocation decisions of an airline [28].

Airlines are constantly challenged to provide the best choice of air travel to their passengers, while operating in a landscape of varying economic conditions, changing passenger preferences, and logistical constraints of their operations [29]. The range of choices available to passengers has shown a great increase, with the emergence of low-cost airlines [30]. Low-fare airlines often offer travel options that involve certain trade-offs, such as using airports that are further from city centers, taking less direct routes, and requiring more connections or layovers. These additional options create a wide variety of choices for passengers. The preference of passengers over these choices is influenced by a variety of factors, making traveler choice of air service a complex issue [31].

The airline industry has been facing significant changes in the past years, with a great expansion in the types of services offered to customers. With low-cost carriers offering lower prices in exchange for comfort and service, new entries to the low-cost market are challenged to provide new and different services as a strategy to differentiate from their competitors [30]. On the other end of the spectrum, niche markets are established by airlines offering a wide variety of high-end services [32]. Despite innovations throughout the service spectrum, customer satisfaction with airline services has reached an all-time low. As a result, it has become more critical and challenging to understand passenger preferences, priorities, and price points, and to develop reliable market and forecasting tools [32].

Airlines compete in a price-sensitive market, hence customers are more likely to choose an airline that offers the lowest price for a given route [33]. As a result, competition is high in this market for all involved airlines [34]. An airline's pricing model is influenced by numerous factors, making it impractical to always offer the lowest prices in an attempt to capture a larger market share [34]. Therefore, pursuing differentiation becomes an essential strategy for many of these airlines [35]. It is crucial for airlines to understand the various factors that influence customers when choosing one airline over another. This underscores the importance of integrating the passenger perspective in the organizational processes of airlines, such as planning, network design, and other strategic decisions through passenger preferences.

1.5. Knowledge Gap

Academic literature has explored the mitigation of the climate impact of aviation through various studies. Three main research directions are identified that contribute to the mitigation of the climate impact of aviation [25]: sustainable energy resources, aircraft design and performance improvements, and operational improvements. The first two research directions have long been studied in the aviation industry [26]. The use of hydrogen-powered aircraft or the implementation of new aircraft designs could take more than a decade to progress [27], and it is not anticipated that they will play a role in efforts to reduce the environmental impact of aviation [25]. It is vital that aviation stakeholders, mainly airlines consider the climate impact of their operations in their decision-making process. This objective can be accomplished through the implementation of operational improvements tailored to the existing fleet and technologies, aiming to mitigate the climate impact. Utilizing an airline's network is a practical means of achieving this goal.

The network planning problem of an airline considers decisions on the route, time, and fleet based on passenger demand. Airline demand is influenced by passenger preferences, encompassing factors such as preferred travel times and route choices [36]. Passengers exhibit a preference for flying during morning and evening hours, prompting airlines to schedule flights accordingly. The flexibility of passengers is a critical factor, as some may consider adjusting departure times, while others prioritize changing airlines over altering their preferred departure time. A comprehensive network planning model must account for these aspects. Furthermore, passenger sensitivity to travel times, emphasizing a preference for direct and shorter flights over connecting and longer itineraries, should be considered when designing the network of an airline.

Airline network design mainly has an economic perspective and aims at creating a minimum-cost plan driven by market demand [12]. The network design includes the determination of flights to be included in the network, establishing flight frequencies for origin-destination pairs, timetable creation, and passenger routing. Even though the literature on green aviation has shown progress [8], most models are built with operation research techniques and only optimize on economic targets [12]. Given the imperative to mitigate the environmental impact of aviation, there is a consideration of whether an individual airline could reduce its climate impact by operational improvements in terms of structural changes to its network. The consideration of climate impacts has been explored to some extent in the literature when addressing the network planning problem; however, the influence of passenger preferences is often lacking in these studies.

Extensive academic research has been conducted to explore the impact of climate and passenger preference considerations on airline network design. Despite the inherent multi-objective nature of airline network design, only a limited number of studies address multiple objectives in this context [8]. The studies included in the literature review can be found in Table 1.1 containing the studies, their respective approaches, climate objectives, indication of a network design approach, and whether passenger preferences are considered.

Authors	Consideration of network design	Approach	Climate objective to minimize	Consideration of passenger preferences
Noorafza et al. [26]	Yes	Multi-objective optimization for network design& fleet allocation	Average temperature response	No
Parsa et al. [8]	Yes	Multi-objective optimization to establish hubs	Greenhouse gas emissions, fuel consumption, noise pollution	No
Rosenow, Lindner, and Fricke [37]	Yes	Trajectory optimization	NOx emissions and fuel consumption	No
Kölker, Santos, and Lütjens [36]	Yes	Optimization for scheduling and aircraft rotation	-	Yes
Braun et al. [12]	Yes	Mixed integer optimization for network design	Near-surface temperature change	No
Bower and Kroo [38]	No	Multi-objective optimization for aircraft design	CO_2 , NO_x emissions	No
Khoo and Teoh [39]	No	Bi-objective optimization for aircraft acquisition	Green fleet index with emission, noise, fuel	No
Roskopf, Lehner, and Gollnick [40]	No	Multi-objective optimization for fleet development & composition and employment	NO_x emission	No
Müller, Kieckhäfer, and Spengler [41]	No	Optimization for fleet planning	CO_2 emissions	No
Ho-Huu et al. [42]	Yes	Multi-objective optimization for route allocation	Noise, fuel, burn, flight frequency	No
Kühlen et al. [43]	Yes	Simulation for fleet development and aircraft route assignment	Average temperature response	Yes

Table 1.1: Authors, consideration of network design, approach of study, climate objective and consideration of passenger preferences of the studies included in the literature review

Noorafza et al. [26] developed a climate-aware network design through a multi-objective framework that minimizes average temperature response (ATR). The climate-aware network is assessed in terms of operational improvements such as intermediate stopovers and lower flight altitudes for three different airlines. Parsa et al. [8] introduced a new mitigation measure to achieve environmental targets of aviation through minimization of greenhouse gas emissions, fuel consumption, and noise in the design of an airline hub-and-spoke network. A mixed-integer programming model is developed for a hub location problem that considers the fleet composition. Rosenow, Lindner, and Fricke [37] developed a cost and climate minimisation network that optimizes flight trajectories. First air traffic network is considered by comparing a network that minimizes fuel and climate costs of latitude-dependent effects of NO_x to only a fuel burn optimized network. Then lateral trajectory optimization is done to find horizontally the shortest flight path with respect to climate costs. Within this optimized routing structure, vertical trajectory optimization is done.

Braun et al. [12] considers both economical and climate targets through the integration of near-surface temperature change that is induced by emissions along the flight trajectories. The study did not delve into the details of how the network is effected by passenger connections and interdependencies of network decisions and flight schedules. Bower and Kroo [38] took a different approach to consider the climate impact and used a given route network to design aircraft by minimizing direct operating costs, CO_2 emissions and NO_x emissions. Khoo and Teoh [39] investigated an airline's compliance with standard requirements in terms of emission, noise, and fuel consumption through a bi-objective dynamic programming model to find optimal aircraft acquisition. Roskopf, Lehner, and Gollnick [40] optimized the fleet composition, fleet development, and fleet employment of an airline for a 10-year planning horizon considering NO_x emissions. The model is used to analyze the trade-offs between economic and

environmental targets through user defined weights. Müller, Kieckhäfer, and Spengler [41] optimized the fleet size and composition of an airline by considering purchase of new aircraft or retrofits to the existing fleet. CO_2 emission constraints are taken into account to analyze fleet planning decisions. Ho-Huu et al. [42] considered the network design in terms of designing new routes and allocating flights to these routes while minimizing the number of people annoyed, fuel burn, number of people exposed to certain noise levels, and number of aircraft movements.

The literature review highlights a significant gap in knowledge within airline network design concerning climate impacts and passenger preferences. Notably, passenger preferences are absent in multi-objective models addressing both economic and environmental targets. Kölker, Santos, and Lütjens [36] solved the airline network planning problem based on passenger decision criteria including preferred departure time, and travel time but did not consider the climate impact. On the other hand, Kühlen et al. [43] incorporated passenger itinerary preferences into their simulation model, comparing scenarios with and without a new mid-range aircraft to assess potential reductions in aviation climate impact [44]. Nevertheless, it's crucial to emphasize that the climate impact of the existing network was not optimized in this study. Literature in this field often lacks a comprehensive focus on all three objectives: cost, environment, and passenger preferences.

1.6. Research Questions

The findings from the conducted literature review have brought attention to an evident scientific gap. The identification of the following research question aims to address this:

How can airline network design be cost-optimized with respect to climate impacts and passenger preferences?

Following sub-questions are formed to answer the main research question:

Sub-question 1: *What specific criteria is there to model and quantify the climate impact within the context of airline network design?*

This sub-question delves into identifying and understanding the specific criteria essential for modeling and quantifying climate in airline network design. It aims to explore the factors, parameters, or metrics that play a crucial role in assessing the environmental implications of different network configurations. By addressing this question, the research aims to establish a comprehensive understanding of the climate impact assessment criteria, which will subsequently guide the formulation of the optimization model.

Sub-question 2: *What specific criteria within passenger preferences, such as departure times and travel routes, should be incorporated into the airline network design process?*

Sub-question 2 aims to identify specific criteria within passenger preferences that hold significance in the context of airline network design. The objective is to identify and understand key factors influencing passengers choices, such as preferred departure times and travel routes. By addressing this question, the research aims to establish a comprehensive understanding of the passenger preference criteria, which will subsequently guide the formulation of the optimization model.

Sub-question 3: *How can an airline network with hubs be modeled to minimize costs?*

Sub-question 3 seeks to investigate the fundamental objectives and cost considerations that play a role in the domain of airline network design. It investigates different modeling approaches for airline network design. Considering the environment and passenger criteria, it aims to assess the current models in literature and how they can be used to guide the formulation of the optimization model of this research.

Sub-question 4: *How can an optimization model be developed to consider costs, climate impacts, and passenger preferences in airline network design?*

This sub-question builds on the outputs from the first three sub-questions, leveraging insights gained from climate and passenger criteria. Building on the foundations laid by the preceding sub-questions, this inquiry focuses on the development of a method tailored for airline network design. The objective is to formulate an innovative optimization model that integrates cost, environmental, and passenger preferences in airline network design.

Sub-question 5: *What are the consequences of incorporating cost, environmental, and passenger preference considerations into airline network design?*

Sub-question 5 aims to analyze the outputs of the model developed in the previous sub-question. Following the development of the optimization model, this sub-question delves into the practical implications and outcomes of implementing different network design strategies.

2

Methodology

This chapter describes the methodology used in this study. In the sections that follow, the research approach with limitations, the research design, and a conceptual model for the multi-objective optimization model are presented.

2.1. Research Approach

The primary objective of this research is to provide strategic insights and decision support for the aviation industry, to achieve an optimal balance between minimizing climate impacts and accommodating passenger preferences in the design of their network structure. This objective can be reached by means of a quantitative research approach.

Adopting a quantitative research approach, this study is focused on the development of a multi-objective optimization model designed to refine the network structure of airlines. The model aids in comprehending and visualizing the interactions among elements within a complex socio-technical system and the consequences of system interventions [45]. The system interventions in consideration are the minimization of climate impacts and cost factors, as well as accommodating passenger preferences within the airline network structure. This holistic approach allows for a nuanced exploration of the trade-offs inherent in striking a balance between environmental sustainability and economic viability, all while catering to the diverse preferences of passengers.

2.2. Research Design

In this section, the research design per sub-research question is discussed and presented with a research flow diagram. A modeling approach is adopted [46], encompassing research steps such as information gathering, model conceptualization, model development, model implementation, and model discussion. Each step is designed to address one or more sub-questions, and the outcomes of each sub-question serves as inputs for subsequent inquiries. Figure 2.1 visualizes the research flow, with steps taken as well as the input and output of each step.

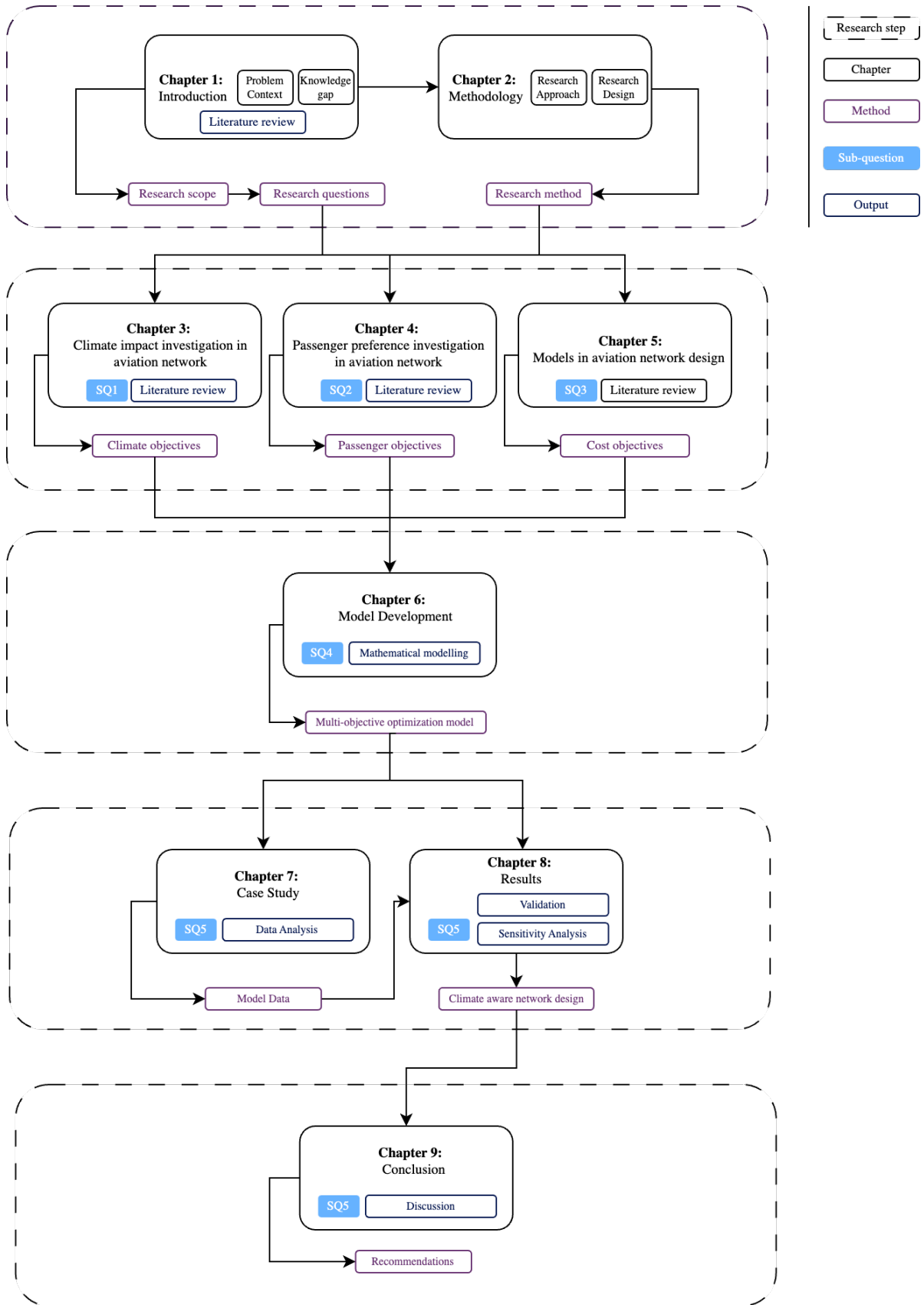


Figure 2.1: Research Flow Diagram

Sub-question 1: This sub-question involves conducting a thorough literature review to identify and comprehend the specific criteria required for modeling and quantifying climate impact in the context of airline network design. By drawing insights from the literature, the research aims to inform the development of criteria relevant to climate impact assessment, ensuring a well-informed and comprehensive understanding. The output is a set of well-defined criteria that can be employed to measure and quantify the climate impact associated with various aspects of airline network design, ensuring a systematic and accurate evaluation of environmental considerations.

Sub-question 2: To address this sub-question, a literature review is conducted, delving into existing research to discern the aspects of passenger preferences that have a significant impact on their decision-making when it comes to choosing flights. The output from this sub-question is the passenger preference criteria that is implemented in the model development.

Sub-question 3: In addressing this sub-question, a comprehensive literature review is conducted to explore and analyze existing models related to the primary objectives and cost considerations inherent in airline network design. By giving a discussion on models considering cost parameters present in literature, the model development is guided that takes into account the environment and passenger preference criteria driven from the previous sub-questions.

Sub-question 4: It is essential to acknowledge that any optimization model is a representation of reality and inherently simplifies the complexities of the aviation landscape. While striving for accuracy and effectiveness, the model serves as a tool to aid decision-making by providing valuable insights into the trade-offs and synergies between minimizing climate impacts and meeting passenger preferences within the constraints of airline network design.

Sub-question 5: This sub-question is addressed through a sequential approach involving two key steps: first, the execution of a case study for data generation, and second, the application of the generated data to solve the developed optimization model.

For the case study, the research aims to examine the applicability and effectiveness of the developed optimization model in a real-world scenario. Ideally, the study would leverage authentic data from an operational airline. However, obtaining real airline data is proved to be challenging. The research has alternative strategies in place. The research utilizes the dataset introduced by O'Kelly [47], a widely used resource in hub location research. This dataset provides information on distances and the number of airline passengers between 25 United States cities in 1970, offering a historical perspective on air travel patterns. The dataset is further introduced in Chapter 7.

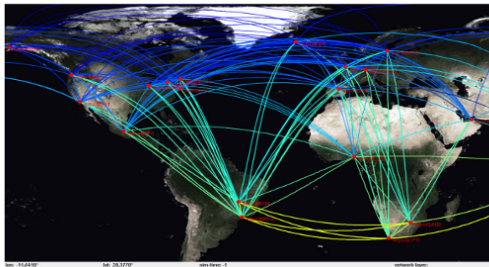
Within the scope of this research, it becomes imperative to consider multiple objectives. The complexity intensifies when these objectives exhibit conflicts, making it challenging to attain a universal solution that satisfies all objectives simultaneously. These problems typically do not have a singular global solution, requiring the identification of a collection of points that adhere to a predefined criterion for optimum [48]. The primary concept in defining an optimal point is that of Pareto optimality, in which the set of Pareto optimal solutions is a set of solutions that are non-dominated [49]. The aim is to identify the Pareto frontier, representing the set of optimal solutions that entails a trade-off between each objective [49].

2.2.1. Airline Network Design

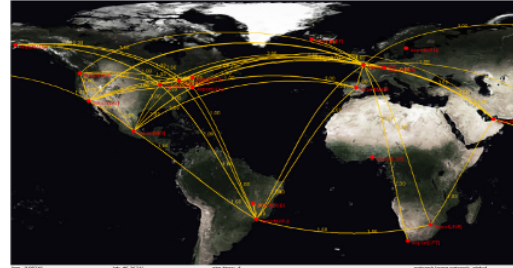
The aviation industry is concerned with the movement of people and cargo through the air from an airport origin to an airport destination [50]. The routing of these origins and destinations is part of the airline network planning process, a strategic activity carefully planned by airlines between five to two years before the scheduled take-off [51]. The airline network planning process is a combination of various interrelated decisions, starting from strategic planning (route planning, fleet planning), tactical decisions (schedule planning, fleet assignment, revenue management), and operating decisions (aircraft routing, schedule recovery) [52]. These decisions have a great impact on an airline's operating profitability and must be taken optimally.

Airline network design can be described by airports connected by flight routes [37]. Three main approaches can be identified that solve these network design problems, Mixed Integer (Non-)Linear Program, heuristics and algorithms from graph theory, and agent-based modeling [53]. Several prior studies

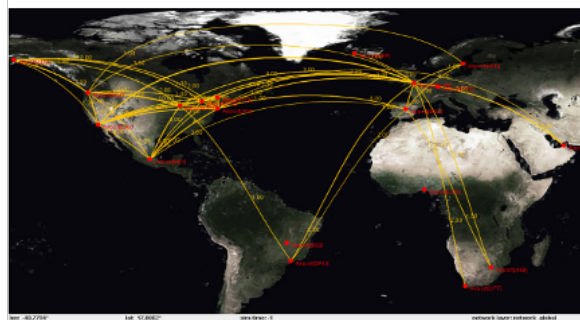
in the literature have focused on constructing networks and flight schedules from the ground up [8, 26, 12]. This ensures that the operational impact of different network design policies can be studied without the influence of a particular airline policy or legacy network structure [8]. The initial optimization of the network solely considers economic targets taken as a reference network, after which environmental targets are introduced to assess potential alterations to the network design [26, 12, 36].



(a) All possible routes [12]



(b) Network layout for economical targets only [12]



(c) Network layout for environmental targets only [12]

Figure 2.2: Network layouts for different objective targets, [12]

Several studies are present in literature that integrate the climate impact into the network design process. Different climate metrics are taken into consideration, such as near-surface temperature change [12] and NO_x emissions [37]. Figure 2.2a depicts all potential routes considered in the study of Braun et al. [12], in which different network designs were produced to assess network profit and network climate impact. By integrating both the economic and climate impact through a weighting metric in the cost function, different network policies are assessed. Figure 2.2b illustrates the network layout when only economic targets are taken into consideration. Notably, when emphasizing environmental targets as shown in Figure 2.2c, the resultant network structure tends to lean towards the northern zone, identified as a less climate-sensitive area. It is claimed that potential reductions in climate impact can be achieved, at the cost of very low profit losses and different network configurations.



(a) Cost optimized network structure A for a given number of nodes and demand, solely considering fuel burn costs [37]



(b) Cost optimized network structure B for a given number of nodes and demand, considering global average climate impact and latitude-dependent differences in the effect of NO_x emissions [37]

Figure 2.3: Cost optimized network structures for different criteria [37]

The airline industry today is highly competitive, with network and trajectory optimization primarily influenced by fuel and time costs [37]. The climate impact of air traffic is also affected by the location of emissions, meaning that the structure of the airline network itself can influence climate effects. The work of Rosenow, Lindner, and Fricke [37] introduces an approach that integrates network and trajectory optimization to simultaneously minimize climate impacts and operational costs. Figure 2.3a shows the result of an airline network only optimized for fuel burn costs. Orange lines represent point-to-point connections and hubs are indicated with black lines. On the other hand, Figure 2.3b shows the climate optimized network, that considers latitude-longitude dependent NO_x emissions. Depending on the flight route, certain connections can impose higher levels of climate impact due to NO_x emissions and are banned when the network is optimized. Colors denote the cost in terms of NO_x emissions, with red: Southeast area most expensive, yellow region: intermediate, and green: Europe cheapest. One notable change in the network structure after the consideration of climate impacts is the movement of one hub from the red region to Europe, allowing the airline in consideration to serve other markets where climate costs are reduced.

The examples of airline network design presented in the literature highlight how the introduction of climate objectives can significantly alter network structures. These findings underscore the critical need for integrating environmental considerations into the traditionally cost-focused network planning process. Studies such as those by Braun et al. [12] and Rosenow, Lindner, and Fricke [37] demonstrate that optimizing networks solely on economic targets often leads to different configurations than those optimized for environmental impact, particularly in terms of NO_x emissions and climate sensitivity of various regions. The climate consideration in this research is determined after conducting a comprehensive literature review, which is undertaken to address sub-research question 1.

Building upon this foundation, the methodology of this research adapts and extends existing hub location models to incorporate environmental and passenger preference objectives alongside economic goals. This adaptation is necessary because traditional models are primarily designed to optimize costs and may not sufficiently capture the complexities introduced by environmental and passenger considerations.

2.2.2. Hub and Spoke Network Design

The routing structure of airlines has undergone significant changes over the past fifteen years, with hub-and-spoke systems taking the lead [54]. The hub-and-spoke system channels traffic through several major facilities known as hubs, using connected routes referred to as spokes. Transshipment involves redirecting flows to an intermediate airport and then onward to another airport, in which the intermediate stop is a hub airport [55]. Past studies in the literature on hub-and-spoke systems are both part of airline economics research as well as operations research/transportation science [18]. These network designs typically emerge in situations where the transportation or traffic from its origin to its destination faces cost constraints or practical limitations that make it impractical to allocate dedicated

transport links for each origin-destination pair [1].

A classic and commonly studied problem is the single allocation p-hub median problem with the restriction that connection between non-hub routes is not allowed [18]. Given a pre-decided number of p hubs in a network, find the set of locations such that each non-hub is connected to a single hub and the total transportation costs are minimized. Typically the flows between nodes are directed through either one or at most two hubs.

Given the efficiency and extensive use of hub-and-spoke network configurations in the airline industry, this research focuses on optimizing these networks by integrating environmental considerations and passenger preferences into traditional cost-driven models. The hub-and-spoke system, which channels traffic through strategically located hubs, forms the backbone of this study's network design. By focusing on this specific network structure, the research aims to explore how the inclusion of environmental impacts and service quality metrics, such as passenger satisfaction with departure times, can refine and enhance traditional airline network designs.

3

Environmental Considerations in Airline Network Design

This chapter addresses the sub-research question: *What specific criteria is there to model and quantify the climate impact within the context of airline network design?* It starts by emphasizing the alarming climate impact of aviation and detailing the greenhouse gases emitted by aviation activities. This is followed by a review of emission reduction strategies found in the literature. Finally, a methodology is introduced to quantify the climate impact of aviation.

3.1. Aviation Impact on Climate Change

All forms of aviation are responsible for releasing greenhouse gases such as CO_2 , NO_x [5]. These play a critical role in accelerating global warming and ocean acidification [24]. Aviation industry not only contributes to this by CO_2 emissions during flight but also through ground airport vehicles, production of energy used in airport terminals, manufacture of aircraft and construction of airport infrastructure [24].

According to the Intergovernmental Panel on Climate Change (IPCC), aviation industry is responsible for 3.5% of the anthropogenic factors of climate change in 1992, and if the current trend persists aviation may be responsible for up to 15% anthropogenic factors of climate change by 2050 [24]. A typical aircraft mostly during cruise state, contributes to climate change in four ways [24]:

3.1.1. Carbon Dioxide (CO_2 Emissions)

According IPCC, CO_2 is the most concerning gas emitted by an aircraft through fossil fuel combustion [24]. Air travel is responsible for 2.5% of global fuel combustion-related CO_2 emissions [56]. According to Golui [24] narrow-body aircraft, which generate 80% of revenue passenger kilometres (RPKs) is responsible for 75% of commercial passenger aircraft consumed jet fuels, and hence 75% of CO_2 emissions.

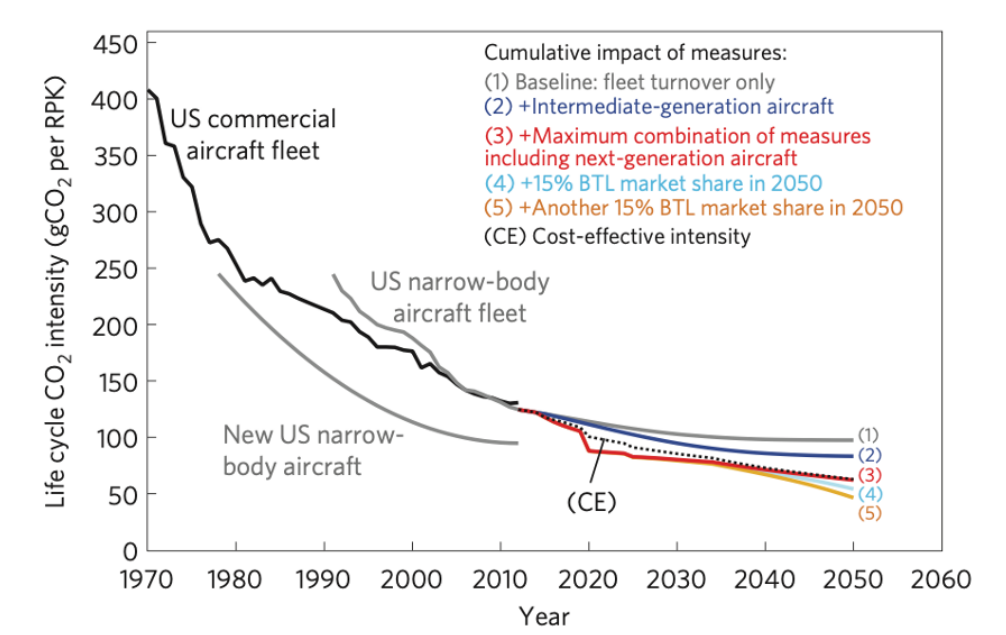


Figure 3.1: Life cycle CO_2 emissions intensity of the US commercial passenger aircraft fleet operating in domestic service (black) and of the narrow-body fleet (grey), historical development (1970–2012) and projections (2013–2050) [5]

Figure 3.1 shows the decadal decline in CO_2 emissions of US commercial passenger aircraft fleet as well as the narrow-body fleet [5]. Due to increased efficiency in aircraft engines, the decline in CO_2 emissions was significant from 1970 to 1980. Afterward, the decline persisted but at a reduced pace due to improvements in engine efficiency, aerodynamics, and utilization of aircraft capacity [57]. According to Schäfer et al. [5], despite past achievements, significant opportunities for further reductions continue to exist, potentially extending to at least until 2050.

3.1.2. Nitrogen Oxides (NO_x)

Non- CO_2 effects from air travel also contribute to climate change [57]. Besides CO_2 and H_2O , NO_x is the most important emission source of aviation and its influence depends on the latitude and altitude of emission, as well as the combustion chamber of the aircraft engine [37]. NO_x emissions from large jet airlines, contribute to forming the ozone (O_3) in the upper tropopause [57]. At higher altitudes, the contribution is much higher and enhances the effect on global warming [57].

3.1.3. Water Vapor (H_2O) and Contrails

Aircraft engines generate which primarily use hydrocarbon-based fuels such as kerosene, generates significant amounts of water vapor from the combustion process. At high altitudes, where commercial aircraft typically operate, the water vapor condenses into tiny liquid water droplets or ice crystals almost instantaneously due to the low temperatures [24]. This rapid condensation forms a visible white trail behind the aircraft, known as a condensation trail, or "contrail." Persistent contrails can spread and form extensive cirrus cloud coverage, and can have warming effects contributing to greenhouse effect [57].

3.1.4. Particulates

The emission of soot (black carbon) and sulfate particles from aircraft engines, although minor in terms of their mass compared to other emissions, has distinct and significant effects on the atmosphere and climate [24]. Soot particles can absorb sunlight, and can contribute to warming of the atmosphere [58]. Sulfate particles are highly reflective and can scatter incoming solar radiation back into space. This scattering effect leads to a cooling influence on the climate [58].

3.1.5. Aircraft Noise

Aircraft noise is generated by an aircraft during its different flying phases. It has more consequences for the surrounding environment of airports. Due to aviation, more than 4 million people in Europe were exposed to noise over 55 decibels [59]. According to FICON [60], hearing loss can begin to occur at 75 decibels. Noise levels during landing and takeoff (exceeding 140 decibels) can have serious health effects such as hearing impairment, hypertension, ischemic heart disease, annoyance, sleep disturbance, stimulated aggression [24].

3.2. Airline Emission Reduction

As highlighted in Chapter 2, the traditional airline planning and scheduling process consists of interdependent strategic to operational stages. Strategic decisions are pivotal in setting the direction for emission levels within the airline industry. While decisions at various levels can influence emission outcomes, it is the strategic decisions that define the boundaries and long-term goals for sustainability efforts. According to Krömer, Topchishvili, and Schön [61], these high-level decisions play a critical role in shaping the emission reduction strategies and the overall environmental impact of airlines. The strategic decisions encompass fleet planning, route planning, flight scheduling, fleet assignment and pricing [61].

Traditional models in literature include multiple stages of airline planning and scheduling process, aiming to maximize profit or minimize costs. The recent model-oriented literature on airline emission reduction is also identified to include multiple strategies of airline planning and scheduling process while mostly aiming to reduce CO_2 emissions [61]. As highlighted in the previous section CO_2 is the most concerning gas emitted by aircraft operations. In literature, CO_2 emissions are tackled in four directions:

- **Aircraft selection and assignment** are addressed in the fleet planning & fleet assignment stages. Aircraft specific characteristics such as fuel efficiency, engine type, and aerodynamic design can have an influence on the emission levels.
- **Network design** is addressed in the route planning & flight scheduling stages. The mix of direct and indirect flights can have an influence on the emission levels.
- **Cruise speed** is addressed in the flight scheduling stage. The speed levels of an aircraft have an influence on the emission levels, as it determines the fuel burn.
- **Aircraft utilization** is addressed in the flight scheduling, fleet assignment and pricing stages. Increasing utilization of aircraft can reduce the total number of flights.

The focus of this study is specifically on airline network design, an aspect that plays a critical role in determining the overall environmental impact of airline operations. While various factors such as aircraft selection, cruise speed, and aircraft utilization are significant in reducing emissions, network design uniquely influences the structure and efficiency of flight routes. By optimizing the network layout—deciding on hub locations, determining the mix of direct and indirect flights, and planning flight frequencies—airlines can substantially reduce unnecessary fuel consumption and emissions [8].

Moreover, network design is foundational to the strategic planning stage, where decisions have long-term implications for sustainability. Adjusting the network design can lead to more direct routes, fewer stopovers, and better alignment with passenger demand, all of which contribute to a more efficient and environmentally friendly operation. Given that network design dictates the flow of air traffic across the airline's entire system, it offers a broad and impactful lever for emission reduction, making it the central focus of this research.

3.3. Modeling and Quantifying Climate Impact

Methodology from EEA [62] can be used to estimate the aircraft pollutant emissions. Figure 3.2 highlights the aircraft operations as identified by EEA [62].

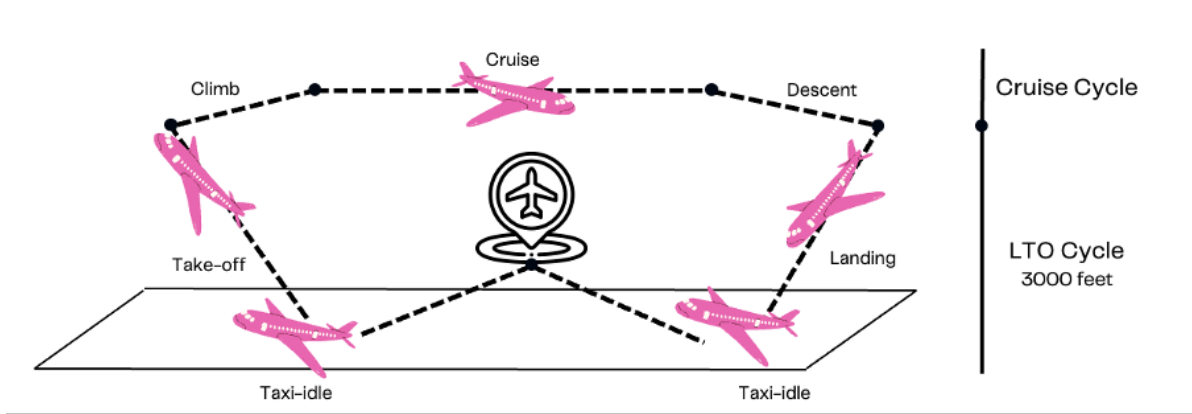


Figure 3.2: Phases of a flight

Aircraft operations can be divided into two cycles:

1. The Landing/Takeoff (LTO) cycle: All activities taking place below 3000 feet during take-off and landing.
2. The Cruise cycle: All activities taking place above 3000 feet during climb, cruise, descent.

Methodology from EEA [62] presents three methods to calculate fuel consumption and emissions from aviation. Tier 3 method is suitable to get an independent estimate of fuel and CO_2 emissions domestic and international air travel [62]. Based on this method, total amount of pollutants emitted by an aircraft can be calculated using:

$$E_p^{LTO} + R_p^C E_p^C d_{ij} \quad i, j \in N \quad (3.1)$$

In a network with N nodes, E_p^{LTO} is the amount of pollutant emitted by an aircraft during LTO cycle, R_p^C is the amount of fuel burned by an aircraft during cruise cycle and E_p^C is amount of pollutant emitted per unit fuel burned during the cruise cycle. d_{ij} is the distance traveled by an aircraft from starting point i to ending point j .

As highlighted in the previous section, CO_2 is the most concerning gas emitted by an aircraft. Equation 3.1 provides a method to calculate the total CO_2 emissions during the LTO and Cruise cycles. Given that these emissions are a function of the distance traveled during the cruise cycle, they can be integrated into the network design process for airlines. Despite a few studies in the literature [36, 12, 8] that optimize airline networks with consideration of climate impact, it is unclear if airlines are actually incorporating this factor into their processes.

4

Passenger Preferences in Airline Network Design

This chapter addresses the research question: *What specific criteria within passenger preferences, such as departure times and travel routes, should be incorporated into the airline network design process?* It begins by a discussion on various types of passenger preferences. The chapter concludes with an analysis of how to integrate these preferences into network design and which specific preferences to prioritize.

4.1. Key Passenger Preferences

Passengers exhibit different preferences for all possible itineraries. On any given day, an airport may be supplied by hundreds of itineraries, that offer passengers a potential way to travel between different destinations [63]. An itinerary is a detailed passenger route, containing information on the leg (flight) or multiple legs connecting an origin-destination pair [36]. Itineraries can be nonstop (with no flight changes), single-connect (one flight change) or multiple-connect (several flight changes). Passenger preferences among itineraries are distinguished by factors such as departure and arrival times, travel routes (including the number of stops), cost considerations, and overall travel experience. These preferences could range from preference to fly at a specific time, with a specific route, and more specific preferences during flight such as food and entertainment [36].

4.1.1. Departure Times

Flight departure times are a critical factor in passenger itinerary choices [63]. It is evident that itineraries with similar departure times share unobserved characteristics that air travelers consider in their selection process [63]. For instance, travelers often have preferred departure times and will compare and contrast the attributes of itineraries that align closely with these preferences. Consequently, itineraries within a specific time period are likely to compete more directly with each other than with those in different time periods.

Departure times are often considered as explanatory variables for itinerary choice modeling in literature [64, 63, 65]. Flight scheduling is influenced by many factors such as airport time slots, ground operations, and fleet sizes [64]. This might lead to passengers not being able to choose their preferred departure time and cause them to experience schedule delays. The choice process can vary between different user segments, and passengers are sensitive to schedule delay [66]. Schedule delay is defined as the sum of frequency delay, which is difference between preferred departure time and closest scheduled departure time, and stochastic delay, which is additional delay if there is no availability in the best scheduled flight [67]. Schedule delay is a critical measure of the convenience of scheduled services and underscores the importance of aligning flight schedules with passenger preferences to enhance satisfaction and optimize airline operations.

4.1.2. Travel Routes

Air passengers prefer routes that include less number of flight legs, and customer satisfaction is affected by travel on multiple links and delays at transit points [68]. A hub-and-spoke network allows passengers to travel between a wide variety of origin-destination pairs, however it also requires them to make at least one stopover if their final destination is not a hub airport. Passengers show high willingness to accept higher fares or increased access time for direct flights [69]. As compared to non-stop alternatives, the hub-and-spoke network can increase the average journey time for a passenger due to extra connecting time at the hub airport [70]. However it can also reduce the schedule delay due to increased frequency of service [67]. Passengers have more options to choose from and are more likely to find flights in their desired departure time.

4.1.3. Travel Time

Departure and arrival times of flights are important, in determining the choice of flights by passengers [71]. Business travelers typically have strict requirements regarding travel time and rarely prioritize lower prices due to their limited flexibility with schedules. Conversely, leisure travelers tend to select the lower-priced option when presented with two acceptable flight choices [72].

4.1.4. Cost Considerations

With the deregulation in Europe, and the emergence of multiple airlines competing on the same routes, passengers are left with more choices in terms of prices [73]. Legacy airlines face cost competition with the emergence of low cost airlines, and have been adapting a low cost strategy by cost-cutting programmes [73]. A more complex mix of choices are now offered by both types of airlines. Low-cost airlines offer value-added services for an additional fee, and legacy airlines have easily adopted this approach, even though their passengers have traditionally expected amenities like drinks, meals, and other comfort items to be included in the ticket price.

Most airline passengers are sensitive to airline travel cost, and to extent of this differs per passenger segments [73]. Business passengers are more likely to consider factors such as reliability, seating comfort, and schedules, for leisure passengers price tend to be the most important factor [74]. Airlines charge a wide range of prices on most routes with different amenities, and however average fares do not differ significantly among similar airlines for the same route[75]. This indicates that passengers might prioritize other aspects such as flight schedules, loyalty programs, convenience, and overall service quality. This highlights the importance of understanding passenger preferences comprehensively, as price alone does not drive their choice.

4.2. Passenger Preferences in Network Design

Not all passenger preferences influence the strategic level of planning, where the airline network is established [36]. It is essential for airlines to understand time-of-day demand, which provides a basis for when to schedule departures and how to distribute flights throughout the day. This demand is affected by passenger choices on travel time and preferred departure time [71]. Passenger preferences on departure times can be integrated into network design by making decisions on flight scheduling.

Other passenger preference dimensions, such as travel routes and travel duration, can also impact the network design process. Passengers tend to prefer routes with the shortest travel time and the fewest stopovers. While travel routes and travel duration have received significant attention in the literature, preferred departure time has garnered considerably less focus [71]. This research focuses on the latter.

The timing of an airline schedule carries inherent value; some flights departing at specific times may be more or less preferred by passengers [71]. It is common to assess the attractiveness of certain flights based on the time of day using a schedule delay variable, which measures the difference between the desired and scheduled departure times. Passengers generally prefer to fly in the morning and evening, prompting airlines to schedule more flights during these peak hours. Passenger flexibility also plays a significant role; some passengers are willing to adjust their departure times slightly, while others may choose to switch airlines if their preferred departure time is not available. Therefore, a comprehensive model of network planning must consider these variations in passenger flexibility and preferences to optimize scheduling and meet demand effectively [36].

A profit-maximizing airline needs to design its network and schedule to minimize both airline and passenger costs [54]. The network choice and scheduling decisions can impact airline costs and passenger service quality [54]. Airline costs refer to the cost of operating the network, while passenger service quality can be measured by the cost incurred by passengers due to travel time, schedule delay, and late arrivals. Minimizing these costs is crucial for an airline's profitability, and the choice of a profit-maximizing network and schedule depends on these costs. It is possible to minimize passenger costs in terms of schedule delay by integrating flight scheduling decisions into network design.

5

Airline Network Modelling Approaches

This chapter addresses the sub-research question: *How can an airline network with hubs be modeled to minimize costs?* It introduces the different hub location problems in airline network design. The hub-and-spoke network design is widely adopted by airlines operating over large geographic areas due to its efficiency in consolidating traffic and optimizing routes. The growing popularity and attractiveness of hub-and-spoke networks in the airline industry have led to an increased interest in solving hub location problems. Prominent hub-location problems, such as the p-hub median problem and the uncapacitated hub location problem, are presented and explained in this chapter.

This research aims to deliver a method that includes cost, environment and passenger preference considerations into airline network design process. Previous chapters on environmental considerations Chapter (3) and passenger preferences (Chapter 4) revealed certain necessities a suitable modeling approach should encompass in order to integrate these considerations to network design. CO_2 emissions are chosen for the environment measurement, and schedule delay is chosen for the passenger preference measurement. In order to measure the total CO_2 emissions and the schedule delay, the model needs to make decisions on the number of flights on each route in the network. This means that it should allow to track separate flows between each and every node in the network. Existing hub location models in literature are introduced and assessed for their applicability.

5.1. Hub Location Problems

The attractiveness and growing popularity of hub and spoke networks in the airline industry, has led to a growing increase in hub location problems and routing policies [18]. Many past studies on transport and economics have explored the economic advantages of hub and spoke networks [54]. In facility location research, discrete hub location problems involve accommodating the traffic between specified origins and destinations through interconnected facilities called hubs [76]. A non-negative flow is assigned to each origin-destination pair, and an attribute like distance, time, or cost is linked to the movement. In hub location problems cost is used to represent the attribute of interest [76]. Hubs are fully connected, and if the cost of movement is a non-decreasing function of distance, the route from an origin-destination is restricted to at most two hubs. Due to economies of scale, the cost rate of movement between hubs is less than the cost rate of other movement in most models [18].

Hub location problems can be defined in an undirected network with $N = (V, A)$, where $V = \{v_1, v_2, \dots, v_q\}$ are the set of nodes that correspond to origins/destinations and potential hubs. Hubs are a subset of the vertices. A non-negative attribute $d(a, b) = d(b, a)$ representing the length of the link $(a, b) \in A$ connecting vertices v_a and v_b is present. This attribute can represent **travel distance, time, cost or some other attribute**. Let c_{ab} be the length of the shortest path between nodes a and b . The cost for movement from non-hub origin node i to non-hub destination node j via hubs k and l are given as $c_{ik} + \alpha c_{kl} + c_{lj}$ where α is the inter-hub discount factor. In the case that $k = l$, there will be no inter-hub

transfer. For each o-d pair represented with (i, j) , there is a non-negative attribute corresponding to the flow from i to j .

A classification of hub location problems can be achieved by defining the following dimensions [77]:

- **Solution domain:** The available nodes of the model, can range from all nodes, to a set of nodes, or a continuous domain on a plane.
- **Objective:** Min-sum objective minimizing total transport costs, or maximisation of profit.
- **Determination of the number of hubs:** If it is a predetermined number, it is exogenous, and if determined by the model it is endogenous.
- **Allocation type:** Single allocation if nodes are allowed to connect to one hub, multiple-allocation if allowed to connect to multiple hubs.
- **Hub capacity:** Capacitated if there is a restriction on the capacity a hub can handle, or uncapacitated if no restriction.

These definitions are used in literature to classify different hub location problems. Following sections will introduce the p-hub median problem and uncapacitated hub location problem (UCHLP). These problems are path-based, meaning that the decision variables indicate the flow over a given path i to j . However, further research has introduced flow-based formulations of these problems. In flow-based formulations, the decision variables indicate the flow between individual segments or legs of a complete itinerary rather than the entire path from i to j .

5.1.1. The p-hub median problem

The p-hub median problem is defined as follows: In a network, given that there are p hubs, find the optimal set of locations such that each non-hub city is connected to a single hub or multiple hubs while minimizing total transportation costs to accommodate a set of flows [18]. The costs of any network depend on the distance between nodes, the amount of flow to be moved across these distances, and the type of link between nodes [78]. P-hub median problem defines N as the set of n nodes of which p are chosen to be hubs. In a p-hub median problem, the following variables are defined:

X_{ijkl} = Fraction of flow from origin i to destination j that is routed via hubs k and l

H_k = 1 if location k is a hub and 0 otherwise

W_{ij} = Flow from node i to node j

c_{ij} = Cost per unit from node i to node j

$C_{ijkl} = c_{ik} + \alpha c_{kl} + c_{kj}$

X_{ijkl} determines the network structure and how the demand of each o-d pair is allocated to hubs. Depending on the attribute of interest c_{ij} can be time, distance or cost. C_{ijkl} is calculated by summing the attribute of interest for taking route i, j, k, l . In between hubs transfer is discounted with α due to economies of scale. Figure 5.1 shows a simple hub-median network, and the resulting weight matrix given in Figure 5.2.

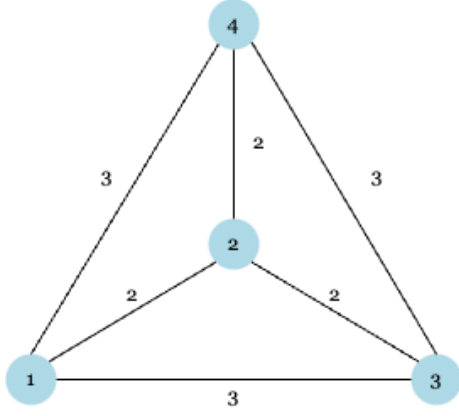


Figure 5.1: Simple hub-median network

W_{ij}	1	2	3	4
1	0	1	4	1
2	1	0	1	1
3	4	1	0	1
4	1	1	1	0

Figure 5.2: Weight Matrix for simple hub-median network

Campbell [76] formulated the p -hub median problem as follows:

$$\text{Minimize } \sum_i \sum_j W_{ij} \sum_k \sum_l C_{ijkl} X_{ijkl} \quad (5.1)$$

The objective function minimizes the transportation cost over all o-d pairs. Equation 5.2 defines that there are exactly p number of hubs.

$$\sum_k H_k = p, \quad (5.2)$$

Equation 5.3 defines H_k to be a binary variable, 1 if node k is a hub and 0 otherwise.

$$H_k \in \{0, 1\} \quad \forall k \in N, \quad (5.3)$$

Equation 5.4 ensures that X_{ijkl} attains fractional values, as it represents the fraction of flow from i to j , routed via hubs.

$$0 \leq X_{ijkl} \leq 1 \quad \forall i, j, k, l \in N, \quad (5.4)$$

Equation 5.5 ensures that all demand from node i to node j is met and is routed through hubs.

$$\sum_k \sum_l X_{ijkl} = 1 \quad \forall i, j \in N, \quad (5.5)$$

Equation 5.6 and Equation 5.7 ensure that the flows from nodes are routed only via hubs. If k or l is a non-hub, the constraint ensures that no demand is routed through these nodes, as it assigns 0 to the respective decision variable.

$$X_{ijkl} \leq H_k \quad \forall i, j, k, l \in N, \quad (5.6)$$

$$X_{ijkl} \leq H_l \quad \forall i, j, k, l \in N. \quad (5.7)$$

If there are no capacity constraints, an optimal solution will have each o-d pair to be routed via the least expensive hub pair, making all X_{ijkl} to be 1 or 0.

Unlike the p-median problem, in which each demand point is assigned to the nearest (least cost) hub [79], in the p-hub median problem single hub assignment does not provide optimality. In the p-hub median problem, instead of having a demand point, there are origin to destination flows. Inter-hub transfer is discounted, and minimizing travel distance does not necessarily lead to a reduction in transportation costs. The inter-hub discount factor α determines the hub locations and spokes in the system [76]. As the value of α decreases, it is beneficial to assign hubs farther away from one another, with fewer spokes. It is more favorable that each node is assigned to its nearest hub. If $\alpha = 0$, inter-hub transfer is not beneficial and each node is allocated to the nearest hub. As the value of α increases, hubs are placed closer together due to increasing inter-hub transfer costs. If $\alpha = 1$, each node is allocated to all p-hubs.

The p-hub median problem has an optimal solution in which all X_{ijkl} are either 0 or 1 [80], meaning all flow between any o-d pair is transferred along one path. Ernst and Krishnamoorthy [80] proved that if an optimal set of hubs given, the problem becomes an shortest path problem between each pair of nodes. The nodes can be allocated to hubs by using all-pairs shortest path algorithm. Given a set of hubs H with size p , for all $i, j \in N$ the all-pairs shortest path algorithm calculates:

$$c[i, j] = \sum_k \sum_l C_{ijkl} X_{ijkl} \quad \forall i, j \in N \quad (5.8)$$

Ernst and Krishnamoorthy [80] developed a heuristic based on the all pairs shortest path algorithm. Starting with a random configuration of H , the heuristic replaces hubs in H with a node in N/H until a better solution is achieved. The new set of hubs in H is used as the starting point of the next iteration of the heuristic. If a better solution cannot be obtained, a different random configuration of H is tried. The number of iterations depends on the problem size. However, for larger problems, the large number of iterations increases computational time extensively [80].

Another approach suggested by Ernst and Krishnamoorthy [80] is to employ the shortest path algorithm on every possible combination of hubs, and the set with the minimum cost is optimal. This algorithm is suitable for small-sized problems, but the complexity increases significantly with the number of hubs and nodes.

Many studies are present in literature that employ the p-hub median problem. O'Kelly [47] presents a quadratic integer program for this problem with two heuristics and utilizes data from the Civil Aeronautics Board (CAB). Following this work, tabu search aiming to get the best solutions for the CAB dataset [81], two heuristics based on greedy exchange [82] and exact solutions with tight linear programming relaxations [78] are introduced.

In the multiple allocation version of the p-hub median problem, it is permissible for a non-hub city to be connected to more than one hub [18]. Work of Aykin [83] tackles both single and multiple allocation hub location problems with several integer programming models. Two networking policies are discussed, nonstrict hubbing in which flows to and from a hub is only chosen if efficient, and strict hubbing in which all flows for a node are channeled from the same hub. In all these models, there is no requirement to monitor the number of passengers on each flight, make decisions regarding aircraft types, or determine the quantity of aircraft for each type to meet the demand (i.e., ensuring sufficient capacity on each route). Ultimately, these models typically assume that the total flow for a specific origin-destination pair will be accommodated through a single path only, as determined by the model's output [18]. A different approach is taken by Jaillet, Song, and Yu [18] which does not assume a priori hub-and-spoke structure, and considers the number of passengers on a given flight as well as choices regarding different aircraft types of different capacity, and number of each aircraft type. Many different paths between o-d pairs are also considered, for instance, a fraction of demand is met through direct and a fraction of demand is met through one-stop flights.

5.1.2. The uncapacitated hub location problem

The uncapacitated hub location problem (UCHLP) differs from the p-hub median problem in two main ways: first, the number of hubs is not predetermined, and second, there is a non-negative fixed cost associated with each potential hub location defined as F_k [76]. This means that in the uncapacitated hub location problem, the objective is to determine both the optimal number and locations of hubs,

taking into account the fixed costs of setting up the hubs, while also minimizing the total transportation cost. The problem can be formulated as:

$$\text{Minimize } \sum_i \sum_j W_{ij} \sum_k \sum_l C_{ijkl} X_{ijkl} + \sum_k F_k H_k \quad (5.9)$$

$$H_k \in \{0, 1\} \quad \forall k \in N, \quad (5.10)$$

$$0 \leq X_{ijkl} \leq 1 \quad \forall i, j, k, l \in N, \quad (5.11)$$

$$\sum_k \sum_l X_{ijkl} = 1 \quad \forall i, j \in N, \quad (5.12)$$

$$X_{ijkl} \leq H_k \quad \forall i, j, k, l \in N, \quad (5.13)$$

$$X_{ijkl} \leq H_l \quad \forall i, j, k, l \in N \quad (5.14)$$

The constraints in the uncapacitated hub location problem are similar to those in the p-hub median problem, but with a key difference: the number of hubs is not predetermined. A capacitated version of this problem can be formalized if the capacities of hubs are limited [76]. Following constraint can be added to convert the above problem formulation to a capacitated location problem:

$$\sum_i \sum_j W_{ij} [\sum_l (X_{ijkl} + X_{ijlk}) - X_{ijkk}] \leq \Gamma_k H_k \quad \forall k \in N \quad (5.15)$$

Each hub at location k can only handle a certain amount of incoming and outgoing traffic, referred to as its capacity and denoted by Γ_k . Equation 5.15 ensures that the total flow for each hub k does not exceed this capacity. The capacity restriction applies to the total traffic entering and leaving the hub. In the formulation by Ebery et al. [1] the following constraint is replaced by Equation 5.16, as only a capacity restriction on the volume of traffic entering a hub is considered:

$$\sum_i \sum_j W_{ij} \sum_l X_{ijkl} \leq \Gamma_k H_k \quad \forall k \in N \quad (5.16)$$

5.1.3. Flow-Based Variations

Both the p-hub median problem and the UCHLP are path-based models. Since both of these approaches are computationally intensive, another problem formulation is suggested by Ernst and Krishnamoorthy [80]. Decision variable X_{ijkl} is removed, and the problem is treated as a multi-commodity problem. Flow originating at each node is treated as a separate commodity. Following variables are defined:

Y_{kl}^i = Total amount of flow of node i that is routed between hubs k and l

X_{lj}^i = Total amount of flow of node i flowing to j via hub l

Z_{ik} = Total amount of flow from node i to hub k

The formulation is given by:

$$\text{Minimize } \sum_i [\chi \sum_k c_{ik} Z_{ik} + \alpha \sum_k \sum_l c_{kl} Y_{kl}^i + \gamma \sum_l \sum_j c_{lj} X_{lj}^i] \quad (5.17)$$

where χ and γ are collection and distribution costs respectively. α is the inter-hub transfer cost.

The model minimizes the cost of travel. Equation 5.18 defines the number hubs to be exactly p .

$$\sum_k H_k = p, \quad (5.18)$$

Equations 5.19, 5.20 and 5.21 are divergence equations for a network flow problem for each commodity i [80]. Equation 5.19 ensures that for each commodity i flow to all hubs must meet the demand from i .

$$\sum_k Z_{ik} = \sum_j W_{ij} \quad \forall i \in N, \quad (5.19)$$

Equation 5.20 ensures that flow for each node i and j through all hubs, meets the demand between i and j .

$$\sum_l X_{lj}^i = W_{ij} \quad \forall i, j \in N, \quad (5.20)$$

Equation 5.21 ensures that flow incoming to hub k from i is equal to the flow outgoing from hub k originating at i .

$$\sum_l Y_{kl}^i + \sum_j X_{kj}^i = \sum_l Y_{lk}^i - Z_{ik} \quad \forall i, k \in N, \quad (5.21)$$

Equation 5.22 and Equation 5.23 ensures no flow travels between non-hub nodes.

$$Z_{ik} \leq \sum_j W_{ij} H_k \quad \forall i, k \in N, \quad (5.22)$$

$$X_{lj}^i \leq W_{ij} H_l \quad \forall i, j, l \in N, \quad (5.23)$$

Equation 5.24 and 5.25 define the domain of the variables.

$$X_{lj}^i, Y_{kl}^i, Z_{ik} \geq 0 \quad \forall i, j, k, l \in N, \quad (5.24)$$

$$H_k \in \{0, 1\} \quad k \in N, \quad (5.25)$$

The above formulation decreases the problem size compared to the p -hub median problem. This is achieved by not tracking each and every flow of traffic between pairs of nodes separately. Instead, the focus is on ensuring that the total flow into each node, combined with any external supply or demand at that node, balances with the total flow out of that node. This method simplifies the analysis by concentrating on the net flow at each node rather than on individual connections between nodes. However it does not allow to track separate flows between each and every node in the network. Moreover, these problems have weaker LP bounds which slows down the optimization [78].

5.2. Hub Location Problems for Airline Network Design

As highlighted by Campbell and O'Kelly [84], it is necessary to extend beyond the classical hub location problems to reflect real-life aspects of airline networks. More real-life elements should be taken into consideration, and models should account for these to provide better insights to the aviation industry. As highlighted in Chapter 1, the rapid expansion of the aviation sector is accompanied by substantial environmental concerns that require serious attention and consideration by the aviation sector. It is important that airlines integrate mitigation strategies to their operational planning to reduce their climate impact [8]. Additionally, it is essential to balance these environmental initiatives with the perspectives of passengers and the airlines' profit maximization objectives.

Hub location problems that are discussed in this chapter are broadly studied in literature. One distinction between these problems is the method of defining the hubs in the network. The p -hub median

problem defines the hubs exogenously, and requires a decision to be made beforehand. In order to make this decision, an initial analysis on the network would be necessary to determine the optimal number of hubs. This can be avoided by adapting the UCHLP, where hubs are determined endogenously through setting up an additional parameter, fixed cost of setting up a hub.

Another distinction is the use of path or flow based decision variables. Flow-based models have smaller problem size due to not tracking each and every flow between all routes, however since their LP bounds are weak, computational time is higher compared to path based models.

For the chosen environmental measurement (CO_2 emissions) and passenger preference measurement (schedule delay), decision on number of flights between each route is necessary. Meaning each and every flow between all pairs of nodes need to be taken into account. Flow-based models are not suitable for this, as they do not allow to keep track of every flow between all pairs of nodes. Adaptation of the UCHLP allows to not have a pre-analysis on the optimal number of hubs and the model makes the decision. Different number of hubs could result in different results for the model of this research. In terms of this, the UCHLP is a better choice than p-hub median problem.

None of the discussed models have integer decision variables, but rather allow to track fraction of demand. A new decision variable that reflects the number of flights is necessary in the adaptation of the UCHLP model. Moreover, to reflect the schedule delay it is necessary to have decisions on when to schedule flights. This can be introduced by defining a time component, t in the adaptation of the model. The changes to existing models are further discussed in the next chapter, where the model of this research is introduced.

6

Model Development

This chapter addresses the sub-research question: *How can an optimization model be developed to consider costs, climate impacts, and passenger preferences in airline network design?* By building on the insights gained from the previous chapters on climate impact and passenger preferences, it introduces the optimization model derived from the modeling approaches available in the literature for hub-and-spoke network design. It describes the model, assumptions, decision variables, objectives, and the constraints of the model. Finally, the method and different scenarios for verifying the model are presented.

6.1. Modelling Approach

As many airlines adopted a hub-and-spoke network structure following airline deregulation in the US and Europe, the model formulation for this research is based on a hub location problem. As highlighted in Chapter 5, hub location problems are well studied in literature and are suitable for the optimization of an airline network design. However, directly applying existing hub location problem formulations is not feasible because this research also addresses passenger objectives and environmental considerations, which are not typically covered in standard path or flow-based models.

The decision variables in the path-based problems represent a fraction of demand, and flow-based decision variables represent the net flow coming or leaving a node. The decision variables in traditional models are unsuitable to adequately capture the environmental impact or reflect passenger preferences of this research. The environmental impact, specifically CO_2 emissions, are dependent on the aircraft type (Chapter 3) and can be quantified based on the number of aircraft traveling a route. Additionally, schedule delay (Chapter 4) can be measured by integrating a time factor that allows scheduling flights for different time intervals. By examining how many flights are scheduled according to passengers' preferred times and how many deviate from this, it is possible to quantify schedule delay.

Therefore, an adaptation of the Uncapacitated Hub Location Problem (UCHLP) by Campbell [76] is necessary to integrate these additional dimensions into the airline network design. Findings from previous chapters regarding passenger preferences and environmental impacts are integrated into the model as specific objectives. By incorporating these factors, the adapted model aims to optimize the airline network not only for operational efficiency but also for a more sustainable and passenger-friendly system.

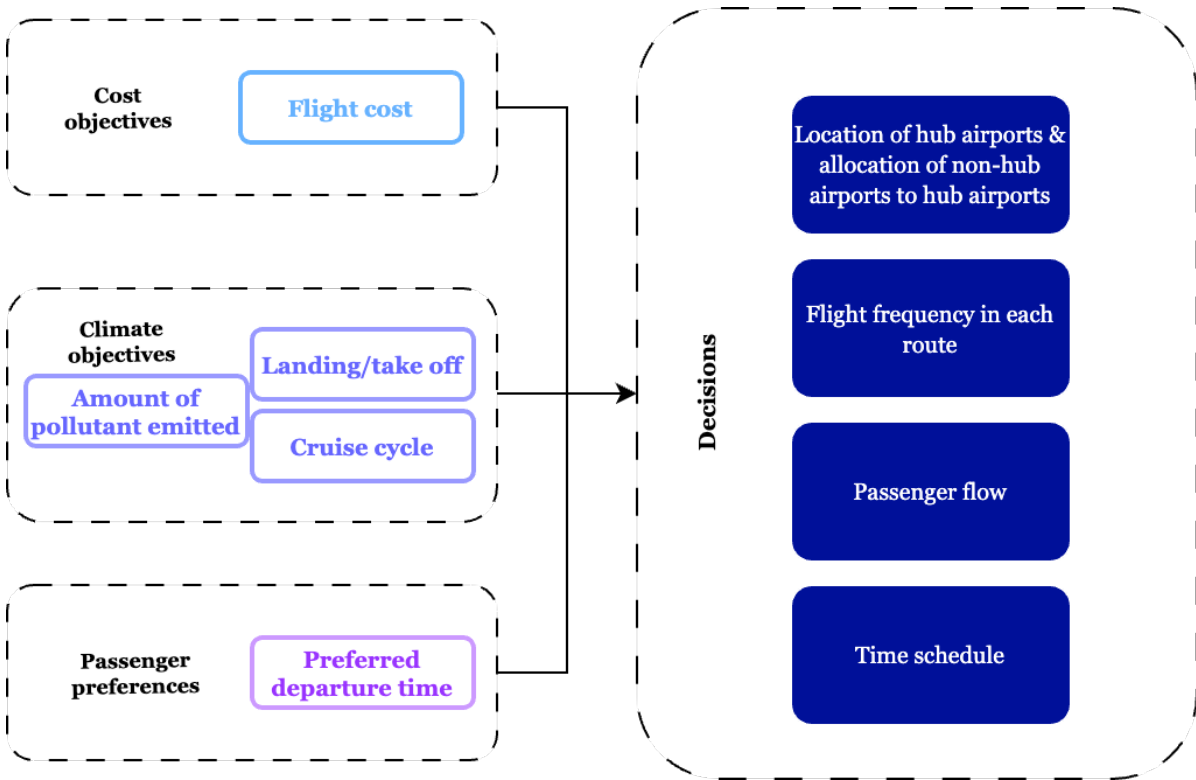


Figure 6.1: Proposed conceptual model for cost optimizing airline network in consideration of climate impact and passenger preferences

Figure 6.1 visualizes the conceptual model that is created to assist the formulation of the optimization problem and considers three factors: cost objective, climate objective, and passenger preferences.

- **Cost objective** is considered in terms of the flight cost of an aircraft per unit distance.
- **Climate objective** is considered using the methodology from of the European Environment Agency [62], which estimates aircraft pollutant emissions [8]. Two cycles of aircraft operations are taken into consideration: Landing/take off (LTO) cycle and Cruise cycle. The LTO cycle includes activities near altitudes lower than 3000 feet during departure and arrival. The cruise cycle includes activities above 3000 feet during climb/cruise/descent.
- **Passenger preferences** are considered in terms of their departure time preferences.

Taking the cost, climate objectives and passenger preferences into account, the model makes decisions related to the location of hub airports & allocation of non-hub airports to selected hub airports, flight frequency and the distribution across different routes, number of passengers on each flight, and planning of flight schedules. The decision variables of the model are tailored to meet the requirements of the objectives. A hub location problem allows the modeling of an airline network to minimize transportation costs by making decisions on the location of hub airports and the allocation of non-hub airports to hub airports. The climate objective, which is dependent on the aircraft type, necessitates decisions on flight frequency for each route. Additionally, passenger preference is dependent on the time of schedule, so this model incorporates decisions on flight scheduling to accommodate preferred departure times.

6.2. Model Formulation

6.2.1. Model Description

The model aims to decide the network design in terms of the location of hub airports, allocation of non-hub airports to these hub cities, flight frequency on each route, and the proportion of demand transferred using each hub for origin-destination pairs. The airline network is represented as a complete graph, $G = (N, A)$ where $N = \{1, 2, \dots, n\}$ is the set of all cities served and $A = N \times N$ is the set of possible

flight routes between these cities. The model uses sets for all airports (N), and considers all possible departure times (T) such as morning, afternoon, or evening flights. Indexes i and j represent origin and destination cities, while k and l denote hub cities, through which flights are routed. Departure time $t \in T$ is used to capture scheduling preferences. The detailed breakdown of these elements is provided in Table 6.1.

Table 6.1: Overview of sets and indexes of the model

Indexes	Description
N	Set of cities
A	Set of possible flight routes ($N \times N$)
T	Set of possible departure times

6.2.2. Assumptions

Similar to hub location problems in literature [47, 1, 76], following assumptions are made:

1. Each non-hub city is connected to at least one hub city, however, there is no direct connection between non-hub cities.
2. Passengers between each non-hub cities can be transferred via two hub cities at most. Passengers between a non-hub city and a hub city can be transferred via one hub city at most.
3. Hub nodes are interconnected at no additional cost.
4. Flights are scheduled to departure in the morning, afternoon or evening time slots.

6.2.3. Decision Variables

The decision variables of the airline network design model, as shown in Table 6.2, extend the traditional framework of existing models in literature by incorporating additional considerations for flight frequencies and departure times. These variables include X_{iklj}^t , which represents the fraction of demand for travel between i to j that is routed through hubs k and l at a specific departure time t . This allows for model to account for different passenger flows at various times of the day. V_{ij}^t denotes the flight frequency on the route from city i to city j at time t , capturing frequency and scheduling of flights. Binary variable H_k indicates whether a city k is designated as a hub (1) or not (0). These enhancements enable model to not only optimize the network's hub locations and demand routing but also to provide flight frequency in each route and time schedule of flights. The additions allow to integrate environmental and passenger preference considerations into network design.

Table 6.2: Overview of the decision variables of the model

Decision Variables	Description	Sets
X_{iklj}^t	Fraction of demand between i to j , that is transferred between hubs k and l at time t	$i, j, k, l \in N,$ $t \in T$
V_{ij}^t	Flight frequency in route i to j at time t	$i, j \in N, t \in T$
H_k	1 if node k is a hub, 0 otherwise	$k \in N$

Table 6.3: Overview of the parameters of the model

Parameters	Description	Units
W_{ij}	Flow of passengers from node i to node j	-
d_{ij}	Distance between nodes i and j	Miles
c^a	Flight cost of an aircraft per unit distance	Dollars (\$)
F	Fixed cost of establishing a hub	Dollars (\$)
E^{LTO}	Amount of pollutant emitted by an aircraft during LTO cycle	Kilograms (kg)
R^C	Amount of fuel used by an aircraft travelling flight distance d_{ij} in the cruise cycle	Kilograms per mile (kg/mile)
E^C	Amount of pollutant emitted per unit fuel burnt during the cruise cycle	Kilograms per mile (kg/mile)
p_t	Proportion that is willing to travel at time t	-
s	Capacity of an aircraft	Seat size
C_k	Capacity of hub k	Number of passengers

The parameters used in the model are presented in Table 6.3.

6.2.4. Objectives

The airline network design problem is formulated as an optimization model. Traditional hub location network design problems mainly minimize total transportation costs in terms of distance traveled. As highlighted in Chapter 5 it is essential to move beyond traditional models that only optimize for costs and develop new ones to more accurately reflect the real-world complexities of hub location problems [8]. Chapter 3 and Chapter 4 revealed additional considerations for airline network design, and these are integrated into the model as objectives.

Economic objective

A profit-maximizing airline needs to minimize airline and passenger costs. Airline costs are reflected in terms of transportation and hub operating costs. The cost objective function is similar to the one from UCHLP formulation, however it considers a different decision variable, number of flights and not the passenger flow. This is introduced to be able to represent environment and passenger preference objectives. The cost objective function from UCHLP is formulated using the decision variables of this model. The first part of the objective function aims to minimize the distance traveled by an aircraft, by considering the flight cost of an aircraft per unit distance c , the distance traveled by the aircraft d_{ij} , and the number of aircraft scheduled for route i to j at time t . The second part of the objective function assigns a fixed cost F for opening a hub at a node, represented with binary variable H_k . The objective function is given in Equation 6.1.

With this economic objective, it is possible to estimate transportation costs more accurately compared to the UCHLP. The UCHLP does not consider traveling costs for aircraft and only minimizes the distance traveled per passenger. However, for an airline, optimizing their network by minimizing transportation costs for aircraft is more beneficial than minimizing the distance a passenger travels. For instance, if there are 150 passengers and an aircraft with a capacity of 100, minimizing the distance these passengers travel does not necessarily reduce costs, as two aircraft would still be needed. Therefore, it is crucial to minimize the total distance traveled by the aircraft, not just the passengers, to achieve cost-effective operations.

$$\text{Minimize } c^a \sum_i \sum_j d_{ij} \sum_t V_{ij}^t + F \sum_k H_k \quad (6.1)$$

Environmental objective

As discussed in Chapter 3, the rapid growth of aviation is leading to an increase in emissions of numerous pollutants. CO_2 is the most concerning gas emitted by an aircraft. Methodology from EEA [62] allows to calculate the total amount of pollutants emitted by an aircraft, by considering two different cycles of aircraft operations: the Landing/Takeoff cycle and the Cruise cycle.

The objective function aims to minimize the total amount of CO_2 emitted by an aircraft. This is calculated by summing the total amount of CO_2 emitted by an aircraft during the LTO cycle and the amount of fuel used by an aircraft traveling flight distance d_{ij} in the cruise cycle multiplied by the amount of CO_2 emitted per unit of fuel burnt during the cruise cycle. This is multiplied by the total number of flights scheduled. The objective function is given in Equation 6.2

$$\text{Minimize } \sum_i \sum_j (E^{LTO} + E^C R^C d_{ij}) \sum_t V_{ij}^t \quad (6.2)$$

Passenger preference objective

In a highly competitive market, airlines must understand their customer's needs and expectations. As discussed in Chapter 4 in detail, it is critical for airlines to understand passenger preferences and priorities, and integrate the passenger perspective in their organizational decisions. This can be achieved by the integration of passenger preferences into the network design process. Passengers exhibit many different preferences, but not all has an influence on the strategic level of planning.

Preference on departure times is selected to reflect the passenger perspective, and the objective function aims to minimize schedule delay of passengers. As discussed in Chapter 4, time-of-the-day demand is an essential metric for airlines, because it provides information on when to schedule departures and how to distribute flights in a day. This demand is affected by passenger preferences on travel time and preferred departure time. It is possible to integrate preferred departure time into this model by adding time interval t to the decision variable representing flight frequency in each route.

The choice to focus on departure times rather than travel times is driven by several factors. First, departure times are a critical factor in passenger satisfaction, as they directly impact passengers' schedules and convenience. Passengers often prioritize flights that fit well with their daily routines, making departure times a key determinant in their flight choices. Second, while travel time is important, its influence is more operational and less strategic compared to departure times. Travel times are generally fixed once routes and aircraft are chosen, whereas departure times can be adjusted to better match passenger demand patterns. This flexibility in scheduling allows airlines to optimize their operations and improve customer satisfaction simultaneously.

Schedule delay is the difference between the preferred departure time and the actual departure time. In the model, this is measured in terms of the deviation in number of flights. The parameter p_t , the proportion of demand of passengers that are willing to travel at time t , is introduced to integrate the departure time preference of passengers into the model. The objective function aims to distribute the number of flights according to the departure time preferences of passengers. This is achieved by minimizing the squared difference between the actual scheduled number of flights going from node i to node j at time t and the desired number of flights going from node i to node j at time t that accommodates passenger preferences.

Due to the formation of constraints the model schedules daily flights. This is explained further in the next section. This objective function forces flights to be scheduled separately for each time period t , while accommodating passenger preferences for departure times. The objective function is given in Equation 6.3.

$$\text{Minimize } \sum_i \sum_j \sum_t (V_{ij}^t - p_t \sum_t V_{ij}^t)^2 \quad (6.3)$$

6.2.5. Constraints

The constraints of the model are adapted from the UCHLP with additional ones. This subsection will introduce the constraints and explain the rationale behind them. The constraints ensure that the flights are scheduled daily when only optimized for economic and/or environmental objectives. This is achieved by summing all the constraints for time periods t , to force the model to consider one time

period for each route and this is taken as the daily flight schedule. Description of the parameters that are used in the constraints can be found in Table 6.3.

Constraint 6.4 ensures that all demand between o-d pairs (i, j) is met and routed through some combination of hubs k and l . It guarantees that the entire demand from i to j is fully satisfied by distributing it through various hub pairs in consideration. This is a typical constraint in the uncapacitated hub location problem [76].

$$\sum_k \sum_l \sum_t X_{iklj}^t = 1 \quad \forall i, j \in N, i \neq j \quad (6.4)$$

Constraints 6.5 and 6.6 ensure that the flow between any o-d pair (i, j) is assigned to hubs. Only operational hubs ($H_k = 1$ or $H_l = 1$) hubs are used for routing the demand. These constraints prevent having non-hub routes. The constraints are typical for the uncapacitated hub location problem [76].

$$\sum_l \sum_t X_{iklj}^t \leq H_k \quad \forall i, j, k \in N, i \neq j \quad (6.5)$$

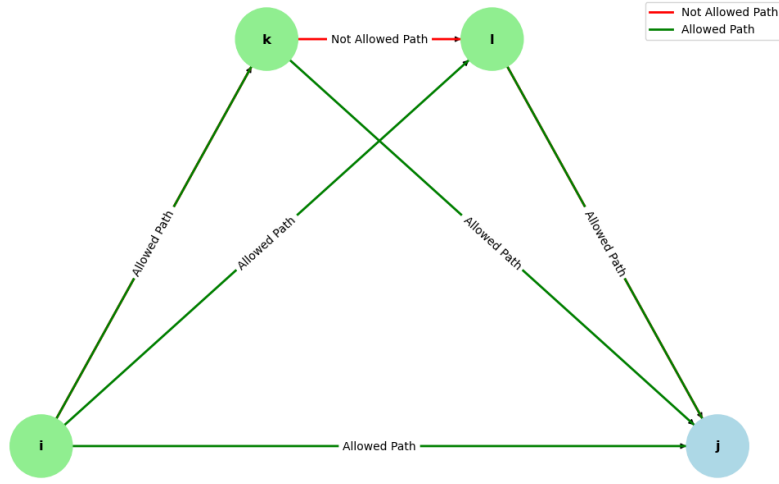
$$\sum_k \sum_t X_{iklj}^t \leq H_l \quad \forall i, j, l \in N, i \neq j \quad (6.6)$$

Constraints 6.7 and 6.8 ensure that if the starting or ending node is a hub ($H_i = 1$ or $H_j = 1$ respectively), then the number of transfers can at most be 1. This means that flow can never be transferred between three hubs. This is not covered in UCHLP. It is added to decrease stopovers and for operational efficiency, as a transfer between three hubs is not ideal for passengers.

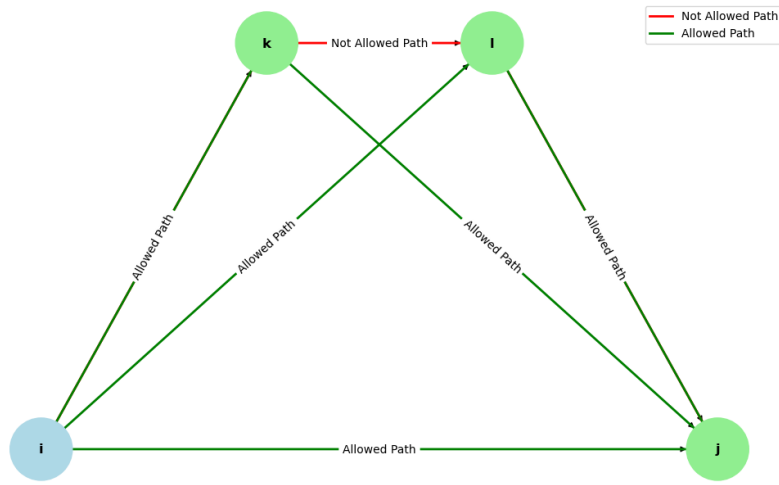
$$\sum_l \sum_{k, i < k} \sum_t X_{iklj}^t + H_i \leq 1 \quad \forall i, j \in N, i \neq j \quad (6.7)$$

$$\sum_k \sum_{l, l < j} \sum_t X_{iklj}^t + H_j \leq 1 \quad \forall i, j \in N, i \neq j \quad (6.8)$$

A simple example illustrating these constraints is given in Figure 6.2. Hub nodes are shown in green and non-hub node is shown in blue. Figure 6.2a shows the case when the starting node i is a hub, then it is only allowed for passengers to travel to j through either directly or through hub k or hub l . When the ending node is a hub as shown in Figure 6.2b, then passengers are only allowed to reach hub j through either directly or through hub k or hub l .



(a) Illustration of constraint 6.7, when starting node is a hub



(b) Illustration of constraint 6.8, when ending node is a hub

Figure 6.2: Illustration of allowed and not allowed paths in the case of 3 hubs

Constraint 6.9 ensures that there is enough seat capacity for all the passengers who want to travel on flights between i to j . Flights from i to j need to have capacity for all passengers that will use this route to reach their destination. The constraint accounts for all these passengers by considering all possible path options that include the link i to j . The constraint ensures that all daily demand is taken into account, and flights are scheduled for a day. Only when the model is optimized for passenger preferences, the flights are scheduled per time interval t , and the sum of flights per time interval t from i to j satisfies the daily demand.

$$\sum_t \left(\sum_k \sum_{l, l \neq k} W_{il} X_{ijkl}^t + \sum_k \sum_{l, l \neq k} W_{kl} X_{kijl}^t + \sum_l \sum_{k, k \neq j} W_{kj} X_{kl ij}^t \right) \leq s \sum_t V_{ij}^t \quad \forall i, j \in N, i \neq j \quad (6.9)$$

Constraints 6.10 and 6.11 ensure that the number of flights from a hub and to a hub does not exceed the capacity of that hub. This provides an upper limit to the number of flights that can be scheduled. These constraints are particularly important when optimizing for passenger preferences, as they provide necessary boundaries for the number of flights. This is essential because the optimization objective focuses on minimizing the deviation in flight schedules rather than on cost or distance. These constraints

are only implemented when optimizing for the passenger preferences to provide a realistic upper limit to the number of flights, and are not necessary when optimizing for other objectives. The capacity calculation for hubs are discussed in the next chapter.

$$s \sum_j \sum_t V_{ij}^t H_i \leq C_i \quad \forall i \in N, i \neq j \quad (6.10)$$

$$s \sum_i \sum_t V_{ij}^t H_j \leq C_j \quad \forall j \in N, i \neq j \quad (6.11)$$

Finally, constraints 6.12, 6.13 and 6.14 defines the domain of the decision variables.

$$0 \leq X_{iklj}^t \leq 1 \quad \forall i, j, k, l \in N, t \in T, i \neq j \quad (6.12)$$

$$H_k \in \{0, 1\} \quad \forall k \in N \quad (6.13)$$

$$V_{ij}^t \in \mathbb{N} \quad \forall i, j \in N, i \neq j, t \in T, \quad (6.14)$$

6.2.6. Difference in Modeling for Different Objectives

For the economic and environmental objectives, the model does not differentiate between time intervals; instead, flights are scheduled for the entire day. Distinguishing between time intervals is only introduced when optimizing for the passenger preference objective. This differentiation is unnecessary for the economic and environmental objectives because the total number of flights is the primary concern. Initially, the model can be utilized for these objectives without imposing a flight schedule across different time intervals. Subsequently, the impact of incorporating passenger preferences for departure times can be assessed by distributing flights throughout the day to meet the segmented demand.

It is also important to note that, since the passenger objective does not consider the distances between nodes or any hub costs, the hubs in the optimal solution are selected arbitrarily when the model is optimized for the passenger objective. When optimizing solely for the environmental objective, hub opening costs are similarly not taken into account; however, the distance between nodes is considered. Consequently, the model is expected to find a network with more hubs and connections compared to when only optimized for the economic objective, as this approach minimizes the distance traveled for each passenger.

Under a purely economic or environmental optimization, 5 flights per day might be sufficient to meet the overall demand. However, when considering passenger preferences, flights need to be scheduled to match preferred travel times (morning, afternoon, evening). This distribution might result in the need for fractional flights to fully accommodate preferences. For example, to meet passenger preferences, it might be necessary to have 2.5 flights in the morning, 1.25 flights in the afternoon, and 1.25 flights in the evening. Since flights cannot be fractional, this would round up to 3 flights in the morning, 2 in the afternoon, and 2 in the evening, leading to a total of 7 flights. Thus, accommodating passenger preferences requires more flights than the minimum number needed to meet demand, leading to underutilization of some flights (e.g., flights that are not fully booked).

6.3. Verification of the Model

A few simple scenarios are used to verify if the model is behaving as expected. A dataset of four nodes, consisting of four cities, is used with varying W_{ij} values in each scenario. Extreme cases with outcomes that can be easily predicted are tested to determine if the model is giving accurate results.

Real distances between cities are taken into account, and can be found in Appendix A Table A.1. A seat capacity of 150 passengers is used for testing. All values of the parameters are provided in Chapter 7 Table 7.1, Table 7.2 and Table 7.3. Fixed cost of establishing a hub, F , is taken as 500,000. The model is first run for only optimizing for the economic objective, followed by the passenger objective and environment objective (Equation 6.1, Equation 6.3, Equation 6.2).

6.3.1. Scenario 1

Testing begins with a scenario where only the demand to and from a single node is considered. Passenger flow values for this scenario are given in Table 6.4.

The first check is to ensure that Baltimore is assigned as a hub since there is only a demand of passengers willing to travel to and from Baltimore. Having any other node as a hub would not be optimal. The second check is to ensure that k and l nodes are hubs and that the flows are only assigned through hubs. Lastly, the model is evaluated to ensure that the number of flights is adequate to meet both the demand from each individual node and the overall total demand.

Table 6.4: Passenger flow values (W_{ij}) between nodes

Nodes / W_{ij}	Atlanta	Baltimore	Boston	Chicago	Total number of passengers
Atlanta	0	600	0	0	600
Baltimore	600	0	600	600	1800
Boston	0	600	0	0	600
Chicago	0	600	0	0	600

The results of this scenario when optimized for the economic objective are presented in Table 6.5, showing the number of flights scheduled in a day. As expected, Baltimore is the only hub, and flights are only scheduled from or to Baltimore. The flights from each node as well as the total flights are sufficient to meet the demand. The results remain unchanged when optimized for the environment objective.

Table 6.5: Results of first scenario, number of flights (V_{ij}) in a day for every route

Nodes / V_{ij}	Atlanta	Baltimore	Boston	Chicago	Total Seat Capacity
Atlanta	-	4.0	-	-	600
Baltimore	4.0	-	4.0	4.0	1800
Boston	-	4.0	-	-	600
Chicago	-	4.0	-	-	600

The model is then optimized for the passenger objective. Since the hubs in the optimal solution are selected arbitrarily when the model is optimized for the passenger objective, the values of H_k from the economic objective solution are defined beforehand. Baltimore is selected as the hub. The results are presented in Table 6.6. As expected, the flights are distributed for the time intervals, according to the passenger preferences and are sufficient to meet the demand.

6.3.2. Scenario 2

An additional scenario is examined where a node experiences zero demand. In this case, there is demand solely associated with one specific node, both in terms of incoming and outgoing demand. Passenger flow values for this scenario are given in Table 6.7.

The evaluation in this scenario proceeds with the following steps: First, verify that Baltimore functions as the exclusive hub. Next, confirm that flows are assigned only to or from designated hubs. Additionally, ensure that no flights are scheduled to or from Chicago. Finally, check if the seat capacity aligns with the specified demand.

Table 6.6: Results of first scenario, number of flights (V_{ij}) for every route for each time period t

Nodes / V_{ij}	Atlanta	Baltimore	Boston	Chicago	Total Seat Capacity
Atlanta	-	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	-	-	600
Baltimore	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	-	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	1800
Boston	-	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	-	-	600
Chicago	-	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	-	-	600

Table 6.7: Passenger flow values (W_{ij}) between nodes

Nodes / W_{ij}	Atlanta	Baltimore	Boston	Chicago	Total number of passengers
Atlanta	0	600	0	0	600
Baltimore	600	0	600	0	1200
Boston	0	600	0	0	600
Chicago	0	0	0	0	0

The results of this scenario are presented in Table 6.8 when optimized for the economic objective. This scenario successfully meets all the specified checks as well. The results are the same when optimized for environment objective.

Table 6.8: Results of second scenario, number of flights (V_{ij}) in a day for every route

Nodes / V_{ij}	Atlanta	Baltimore	Boston	Chicago	Total Seat Capacity
Atlanta	-	4.0	-	-	600
Baltimore	4.0	-	4.0	-	1200
Boston	-	4.0	-	-	600
Chicago	-	-	-	-	0

The results of this scenario when optimized for passenger preferences, with Baltimore defined as the hub are shown in Table 6.9.

6.3.3. Scenario 3

In this scenario, there is demand associated with only two nodes, both in terms of incoming and outgoing demand. Passenger flow values for this scenario are given in Table 6.10.

The expectations for this scenario are as follows: Firstly, Baltimore and Chicago should both be designated as hubs. Secondly, all flights must originate from or be destined to these hubs exclusively. Lastly, the seat capacity must be adequate to fulfill the demand requirements.

Table 6.9: Results of second scenario, number of flights (V_{ij}) for every route for each time period t

Nodes / V_{ij}	Atlanta	Baltimore	Boston	Chicago	Total Seat Capacity
Atlanta	-	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	-	-	600
Baltimore	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	-	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	-	1200
Boston	-	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	-	-	600
Chicago	-	-	-	-	0

Table 6.10: Passenger flow values (W_{ij}) between nodes

Nodes / W_{ij}	Atlanta	Baltimore	Boston	Chicago	Total number of passengers
Atlanta	0	600	0	600	1200
Baltimore	600	0	600	600	1200
Boston	0	600	0	600	1200
Chicago	600	600	600	0	1800

The results of the final scenario are presented in Table 6.11. Initially, the analysis showed that only Baltimore was selected as a hub. This outcome is attributed to the high cost associated with establishing hubs; it was more economical to route transfers through Baltimore to Chicago for other nodes. However, when the hub setup cost was reduced to 50,000 from 500,000, the results aligned with expectations, designating both Chicago and Baltimore as hubs.

Table 6.11: Results of the third scenario, number of flights (V_{ij}) in a day for every route

Nodes / V_{ij}	Atlanta	Baltimore	Boston	Chicago	Total Seat Capacity
Atlanta	-	4.0	-	4.0	1200
Baltimore	4.0	-	4.0	4.0	1800
Boston	-	4.0	-	4.0	1200
Chicago	4.0	4.0	4.0	-	1800

The results of this scenario when optimized for passenger objectives with hubs preselected as Baltimore and Chicago are given in Table 6.12.

Table 6.12: Results of third scenario, number of flights (V_{ij}) for every route for each time period t

Nodes / V_{ij}	Atlanta	Baltimore	Boston	Chicago	Total Seat Capacity
Atlanta	-	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	-	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	1200
Baltimore	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	-	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	1800
Boston	-	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	-	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	1200
Chicago	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	Morning: 2.0 Afternoon: 1.0 Evening: 1.0	-	1800

In all three extreme scenarios, the model performs as expected. Since this is a very small dataset with extreme cases, all objectives can give the same result and network configuration. This consistency arises because the limited and extreme nature of the data does not introduce sufficient variability to differentiate between the objectives. However, this is not expected in a larger dataset with varying passenger demands. Different hub and network configurations could yield better results for different objectives.

7

Data Selection for the Model

This chapter is the first step of addressing the research question: *What are the consequences of incorporating cost, environmental, and passenger preference considerations into airline network design?* It presents the selected case for solving the optimization model. It describes the data analysis process. All necessary values for aircraft, passenger preference, and hub data are described.

7.1. Selected Case

For solving the model data on passenger flows for airlines are required. For this purpose the dataset evaluated by the Civil Aeronautics Board (CAB) and introduced by O'Kelly [47] is used. Many researchers in this field have leveraged this dataset for their studies, and refer to it as the CAB dataset. The dataset was collected during the peak month of 1970, capturing a snapshot of airline passenger flows and distances between 25 major U.S. cities during that time [8]. A visualization of the cities included in the CAB dataset is given in Figure 7.1.



Figure 7.1: CAB dataset

For computational efficiency, 10 cities are selected for the model. As one of the purposes of the model is to decide on a daily flight schedule for an airline, the data for 10 cities is divided by 30 days to get the daily passenger flow. The modified dataset is presented in Figure 7.2. The upper triangle shows the demand of passengers (W_{ij}) between each cities, and the lower triangle shows the distance (d_{ij}) between each cities. A total flow of 33,294 passengers are considered in the model.

295	223	553	1711	239	347	216	187	Houston	
75	107	192	911	52	117	385	Denver	1143.79	
390	129	198	714	103	167	Dallas	663.88	982.74	
206	186	471	1171	243	Cleveland	1009.69	1216.87	94.26	
156	111	199	636	Cincinnati	225.90	794.17	1080.37	238.94	
668	456	1171	Chicago	255.03	311.31	790.12	907.43	237.07	
254	433	Boston	858.33	749.60	556.07	1541.27	1764.79	621.33	
216	Baltimore	369.53	613.04	429.11	312.88	1196.49	1502.14	405.90	
Atlanta	576.96	946.50	597.60	373.81	559.77	709.02	1208.33	603.65	

Figure 7.2: CAB dataset with 10 cities, passenger flows in number of passengers on the top triangle and distances in miles on the bottom triangle

The complete graph with every possible connection is shown in Figure 7.3.

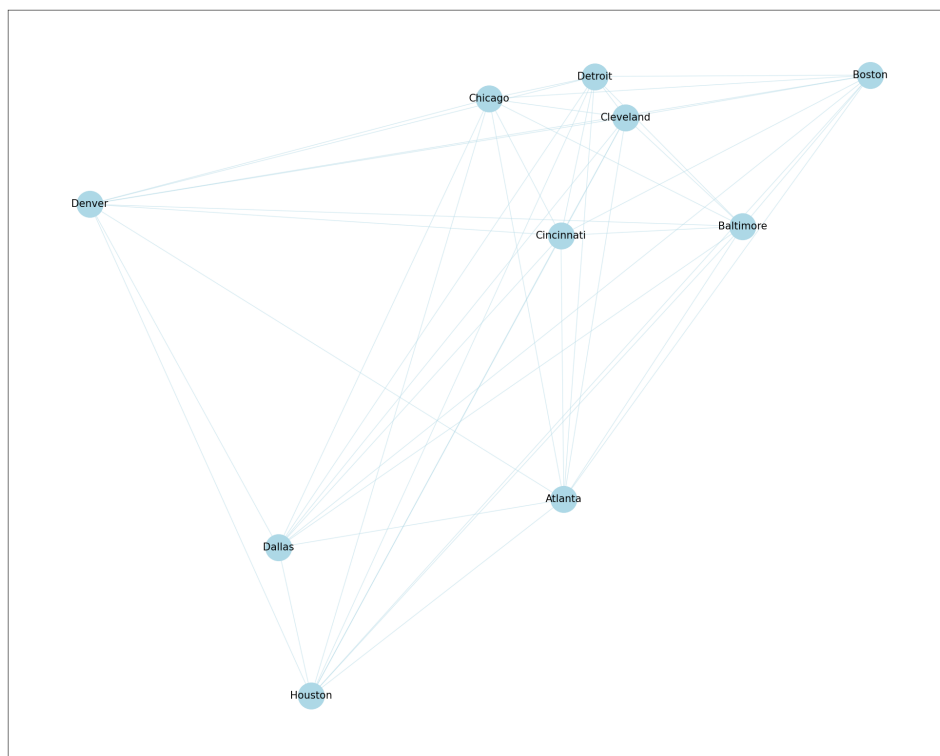


Figure 7.3: Complete graph of 10 cities from the CAB dataset

7.2. Aircraft Data

Table 7.1 provides a summary of the technical characteristics of the selected aircraft. For this case study, an Airbus A320 is selected, a widely used narrow-body aircraft by many airlines [85]. Airbus A320 is one of the most frequently utilized aircraft in both short-haul and medium-haul flights, making it a suitable candidate for this case study. Even though major network carriers that operate on a hub-and-spoke network utilize both narrow and large body aircraft [86], for this analysis only one type of aircraft is used due to data availability.

The emission values are taken from Agency [87]. The guidebook published by Agency [87] provides information on air pollutant emissions, that allows the create emission inventories for different activities. The section on Aviation supported with the Emissions Calculator tool provided the data for this research.

The flight cost of an Airbus A320 per unit distance it travels, as well as the seat capacity is taken from Parsa et al. [8] and confirmed with the manufacturer's website Airbus [88].

Table 7.1: Data for the selected aircraft Airbus A320

Parameter	Description	Value	Source
c	Flight cost	13.534 (\$/mile)	[8, 88]
E^{LTO}	CO_2 emitted during LTO cycle	2.57093 (kg)	[62]
R^C	Fuel used during cruise cycle	2.06855 (kg/mile)	[62]
E^C	CO_2 emitted per unit fuel burnt during cruise cycle	6.51592 (kg/mile)	[62]
s	Capacity of aircraft	150 (number of seats)	[8, 88]

7.3. Passenger Preference Data

Passenger preference on departure times are reflected with parameter p_t , the proportion of passenger demand willing to travel at time t . Three time slots in a day are selected, morning, afternoon and evening. It is assumed that in a day half of the passengers prefer to travel in the morning, and the rest is distributed equally between afternoon and evening flights. Values of p_t are shown in Table 7.2.

Table 7.2: Selected passenger preferences of departure times

	$t = 1$	$t = 2$	$t = 3$
	Morning	Afternoon	Evening
p_t	0.5	0.25	0.25

7.4. Hub Data

Fixed cost of establishing a hub, F is taken to be 500,000 \$. A model from Ebery et al. [1] is used to generate the capacities of nodes. Capacity refers to the number of incoming and outgoing passengers each city can handle if it is selected as a hub in the model.

Given the (x, y) coordinates and volumes of flows W_{ij} for n nodes, capacity C_i for each node can be calculated using Equation 7.1.

$$C_i = \left(n + \frac{3d_i O_i}{5d_m O_m} \right) O_i \quad (7.1)$$

d_i is the distance of node i from the centre of mass of the system. O_i is the total outflow from node i . O_m and d_m are taken as the maximum values of d_i and O_i in the dataset. This model uses these values to generate a capacity for each node that considers both the relative distance of the node from the system's center of mass (indicating centrality) and the node's traffic volume (indicating importance). The potential of a node to handle passenger traffic is given in terms of how important that node is within

the network. A higher capacity for a node (and being more likely to be chosen as a hub) indicates that the node is either very active (with high passenger flow) or centrally located.

By taking the average of the longitudes and latitudes of the cities in the dataset, the center of mass of the network is calculated. The distance from each city to the center of mass is calculated using the Haversine formula. The haversine formula is used to calculate the shortest distance between two points on the surface of a sphere [89]. It is particularly used in navigation problems for calculating distances between geographical coordinates (latitude and longitude) on Earth [89]. Distance between two points can be calculated using Equation 7.2.

$$\text{distance} = 2R \cdot \arcsin \left(\sqrt{\sin^2 \left(\frac{\Delta\text{lat}}{2} \right) + \cos(\text{latitude}_1) \cdot \cos(\text{latitude}_2) \cdot \sin^2 \left(\frac{\Delta\text{long}}{2} \right)} \right) \quad (7.2)$$

where:

- R is the Earth's radius (mean radius = 6,371 km).
- Δlat is the difference in latitudes: $\text{latitude}_2 - \text{latitude}_1$.
- Δlong is the difference in longitudes: $\text{longitude}_2 - \text{longitude}_1$.
- latitude_1 and latitude_2 are the latitudes of the two points (in radians).
- longitude_1 and longitude_2 are the longitudes of the two points (in radians).

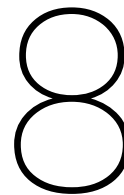
The capacities of each node in terms of the number of passengers they can handle is given in Table 7.3.

Table 7.3: Capacities of each node calculated using the model of Ebery et al. [1]

Nodes	Capacity (in number of passengers per day)
Atlanta	25139
Baltimore	20144
Boston	36737
Chicago	80610
Cincinnati	18080
Cleveland	30480
Dallas	34682
Denver	22793
Detroit	39540
Houston	27786

7.5. Selected Solver

The formulated multi-objective optimization model is implemented using Python 3.9.13. Gurobi 11.0.0 is used to formulate and solve the mathematical model in Python. The interface environment is local Jupyter Notebook 7.31.1. A personal computer of Apple M2 CPU @ up to 3.49 GHz and 8 GB unified memory (RAM) is used.



Results of the Optimization Model

This chapter is the second step of addressing the research question: *What are the consequences of incorporating cost, environmental, and passenger preference considerations into airline network design?* It presents the results of the optimization problem. Firstly single objective optimization is performed. This is followed by multi-objective optimization, that aims to balance the three objectives of the model. Finally, a sensitivity analysis on aircraft seat capacity is presented.

8.1. Single Objective Optimization

An initial analysis is conducted to test the model on each objective, where only one objective is taken into consideration. This is done to achieve the optimal value for each objective. Additionally, this analysis helps to understand the trade-offs involved in prioritizing one goal over others. For this analysis:

- The **economic objective optimization** is when the model is optimized solely for the economic objective.
- The **environmental objective optimization** is when the model is optimized solely for the environmental objective.
- The **passenger preference objective optimization** is when the model is optimized solely for minimizing passenger preference deviation.

Table 8.1: Values of the objectives and number of flights in the optimal solutions for the single-objective optimizations

Attribute	Unit	Economic Objective Optimization	Environmental Objective Optimization	Passenger Preference Objective Optimization
Number of hubs	-	2	7	2 (predefined)
Total number of flights	-	362	260	464
Total cost	Million \$	3.25	5.42	6.60
Total CO_2	Kilotons	2.24	1.91	5580
Passenger Preference Deviation	-	13.25	33.00	0.00

8.1.1. Economic Objective Optimization - S1

Initially, the model is optimized solely for the economic objective, serving as the baseline for comparison. This approach is also assumed to represent the typical airline planning strategy. Since the optimization model's constraints allow for scheduling flights on a daily basis rather than specific time intervals within the day, an additional step is taken to evaluate how well the optimal solution under the economic objective aligns with passenger preferences.

As detailed in Chapter 7, it is assumed that half of the passengers traveling in a day prefer morning flights, one-quarter prefer afternoon flights, and the remaining quarter prefer evening flights. The optimal daily flight schedule derived from the economic objective is then adjusted to accommodate these passenger preferences, without altering the optimal number of flights or any other decision variables.

This analysis aims to assess the performance of the economically optimized solution in meeting passenger preferences, providing a basis for comparison with other objective optimization solutions. The daily flight schedule of the optimal solution can be found in Appendix B Table B.1 and the processed flight schedule for different time intervals of the day can be found in Table B.2.

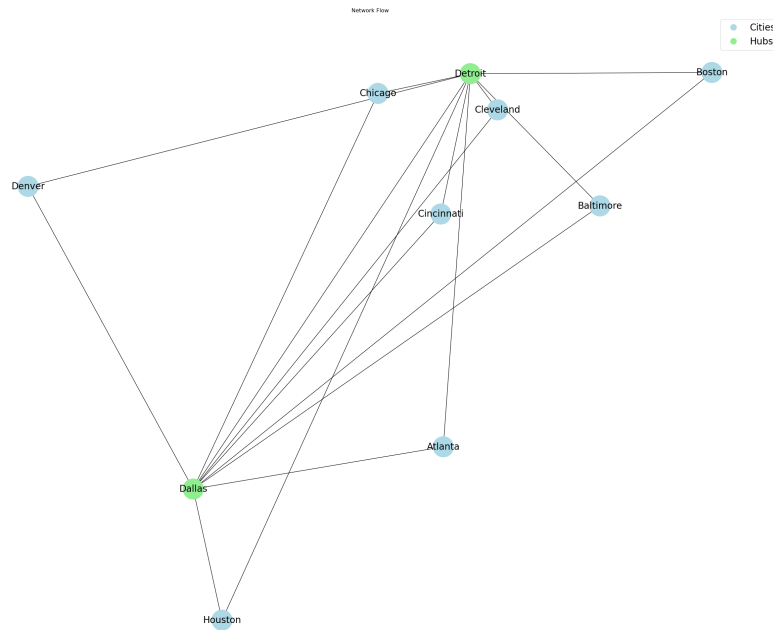
The optimal network design, when optimized for the economic objective can be seen in Figure 8.1a where hubs are shown in green and other nodes in blue. Two hubs are found to be optimal for this objective: Detroit and Dallas. When the demand from each node is analyzed, these cities have one of the highest flows in the network. They are also located in the opposite ends of the network, allowing to facilitate passenger flows across the entire network.

8.1.2. Environmental Objective Optimization - S2

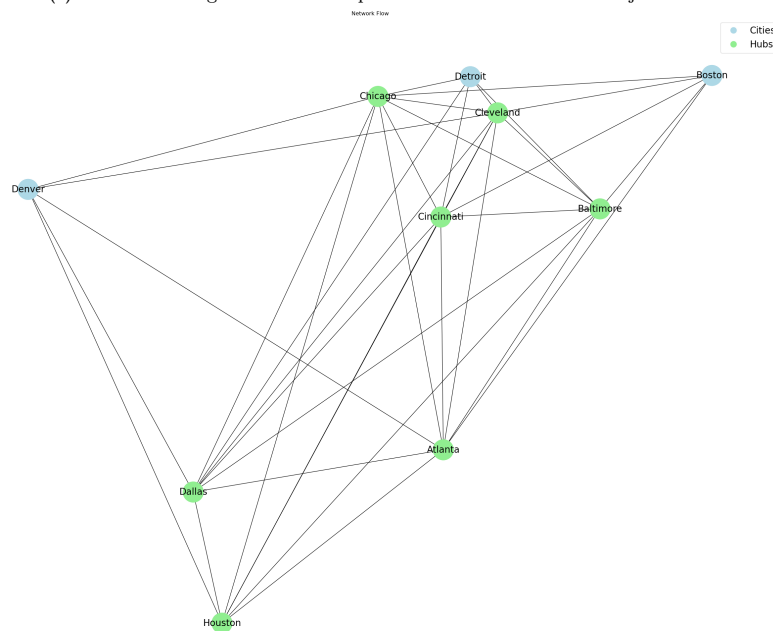
Another single objective solution, only optimizing for the environmental objective is taken into consideration. The resulting network configuration can be seen in Figure 8.1b. Due to the complexity of this objective function and time constraints, the optimization solution is stopped when the solver reaches a 1.70% gap between the best bound and the incumbent solution.

This objective aims to minimize the CO_2 emission of aircraft, which depends on the aircraft type and distance traveled. Since only one type of aircraft is taken into consideration, the resulting network structure only depends on having the shortest possible connections with the least number of flights. Since hub opening costs are not considered in this objective, more hubs compared to the economic solution are opened to allow for more connections, thus less flight distance. Hubs are also concentrated centrally within the network, and not in the boundaries. Central hubs help in reducing the overall emissions by shortening the flight segments. Moreover, routes with more stopovers are meeting less fraction of demand, meaning less passengers need to fly through changing hubs to reach their final destination. Due to having high number of hubs in this solution, less flights are required to accommodate the passenger demand between o-d pairs.

The daily flight schedule of this optimal solution is converted to flight schedule with time intervals according to predefined passenger preferences. Daily flight schedule and flight schedule with time intervals can be found in Appendix B Table B.3 and Table B.4.



(a) Network configuration when optimized for the economic objective



(b) Network configuration when optimized for the environment objective

Figure 8.1: Comparison of network configurations for different objectives

8.1.3. Passenger Preference Objective Optimization - S3

This objective minimizes the deviation from the passenger preferences of departure time. The aim is to have a flight schedule that distributes the number of flights in a day according to predefined passenger preferences for morning, afternoon, and evening flights. Many optimal solutions are possible that can minimize this deviation. Since there are no considerations for hubs or distances between nodes in the objective function, they are chosen arbitrarily in each solution. This objective is initially optimized to minimize the deviation of departure time passenger preferences. The resulting network structure of this optimal solution can be seen in Figure 8.2.

Only one hub is necessary to have a complete network graph, that would satisfy all the constraints. Since there are no restrictions on hubs or distance traveled in the objective function this hub is chosen arbitrarily. To assess the value of optimizing for passenger preferences, the model is initially run without any restrictions on hubs. The results show that the model can achieve zero deviation with various network configurations and hub selections. For consistency and comparability, the hubs identified in the economic objective (Detroit and Dallas) are used for this solution. The model is then optimized again, this time focusing on passenger preferences. For further analysis, the results with predefined hubs are used. The resulting network structure can be seen in Figure 8.3

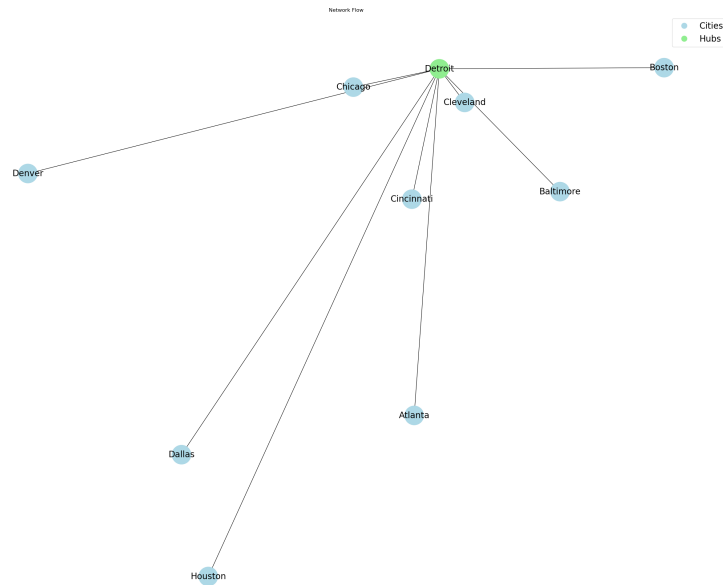


Figure 8.2: Network configuration when optimized for the passenger objective

As expected, more flights are scheduled to accommodate for passenger preferences compared to the economic and environmental solutions, when flights are scheduled per day. As a result, this solution is more expensive in terms of cost and CO_2 emissions.

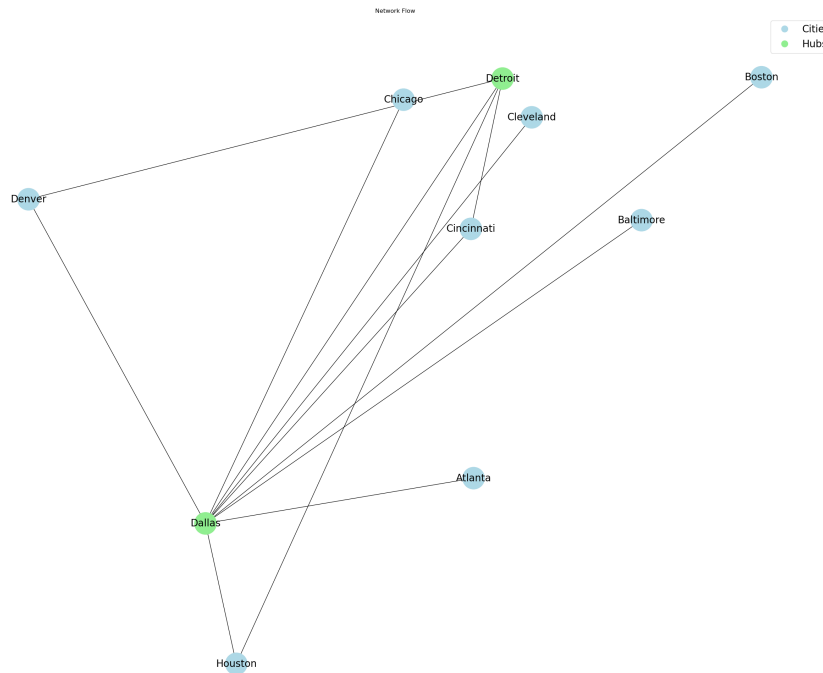


Figure 8.3: Network configuration when optimized for the passenger objective with predefined hubs

8.1.4. Comparison of Different Objectives

The economic objective optimization solution is considered the baseline for comparison, as it represents the typical airline network planning strategy. The changes in cost, CO_2 emissions, and deviation from passenger preferred departure times for the different objective solutions are plotted relative to their changes compared to the baseline, shown in Figure 8.4. These solutions represent different Pareto optimal points, where improving one objective leads to compromises in others.

A different network design that aims to minimize CO_2 emissions is able to decrease emissions slightly but incurs higher costs. This solution has the lowest total number of flights. It is harder to accommodate for passenger preferences because it is more difficult to distribute the number of flights in a day to time intervals. When this distribution is done, it is observed there are many routes with only having one flight in the morning and no flights in the afternoon and evening.

As previously mentioned, deviation from passenger preferences can be reduced to zero using different network designs, as there are multiple optimal solutions. However, when the hubs are preselected, optimizing solely to accommodate passenger preferences results in a significant increase in cost and CO_2 emissions.

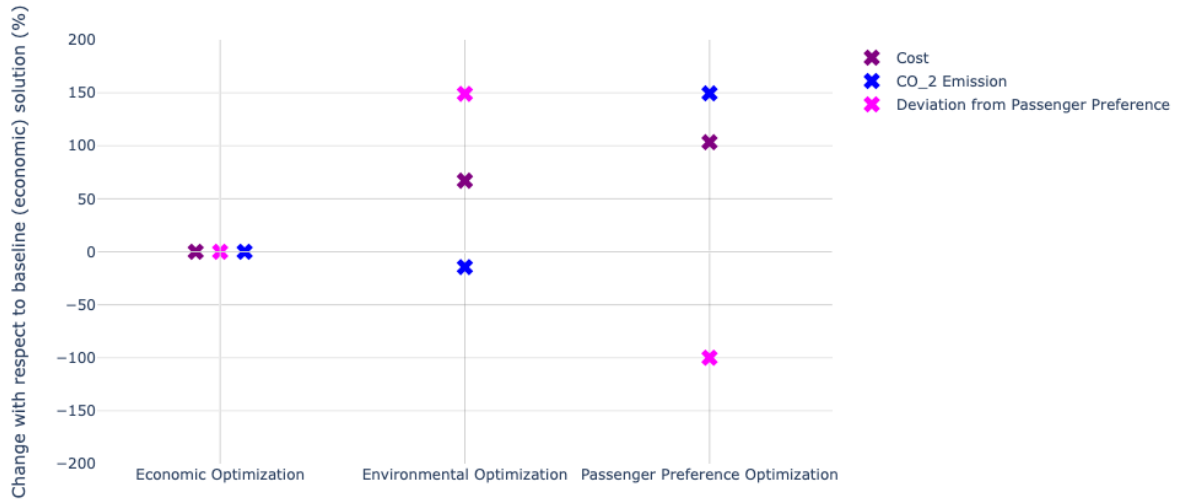


Figure 8.4: Comparison of different single-optimization solutions with baseline (economic) solution (S1)

8.2. Multi-Objective Optimization

The single objective optimizations (S1,S2,S3) revealed that there can be different network configurations when optimized for different objectives. A holistic approach is necessary to implement network designs that minimize costs, CO_2 emissions and accommodate passenger preferences. In this section, multi-objective solutions are tested in which the model is optimized for one objective, and other objectives are added as constraints one by one. The network structure and changing objective values are further analyzed by assigning weights to objective functions and combining them into a single objective.

8.2.1. Economic Objective with Passenger Preference and Environmental Constraints - M1

The model is optimized for the economic objective. As a first step, the passenger objective is introduced as a constraint. Since the passenger preference objective solution (S3) showed that the model can achieve zero deviation with various network configurations, this is tested with when minimizing the economic objective to discover how the cost and network configuration changes from the economic objective solution (S1) when passenger preferences are accommodated. The following constraint is introduced to the model:

$$V_{ij}^t - p_t \sum_t V_{ij}^t = 0, \quad \forall i, j \in N, t \in T \quad (8.1)$$

This constraint aims to minimize the deviation by forcing the model to schedule flights for the defined time intervals according to passenger preferences. Considering that the model is set up in a way that only schedules flights for one day without the time intervals when optimized for economic objective, this extra constraint is necessary to implement passenger preferences. It is not successfully implemented if the objective function of passenger preferences (Equation 6.2) is introduced as a constraint. Constraints for capacity restrictions (Equation 6.10 and Equation 6.11) are disregarded since the economic objective itself already provides an upper limit to the number of flights.

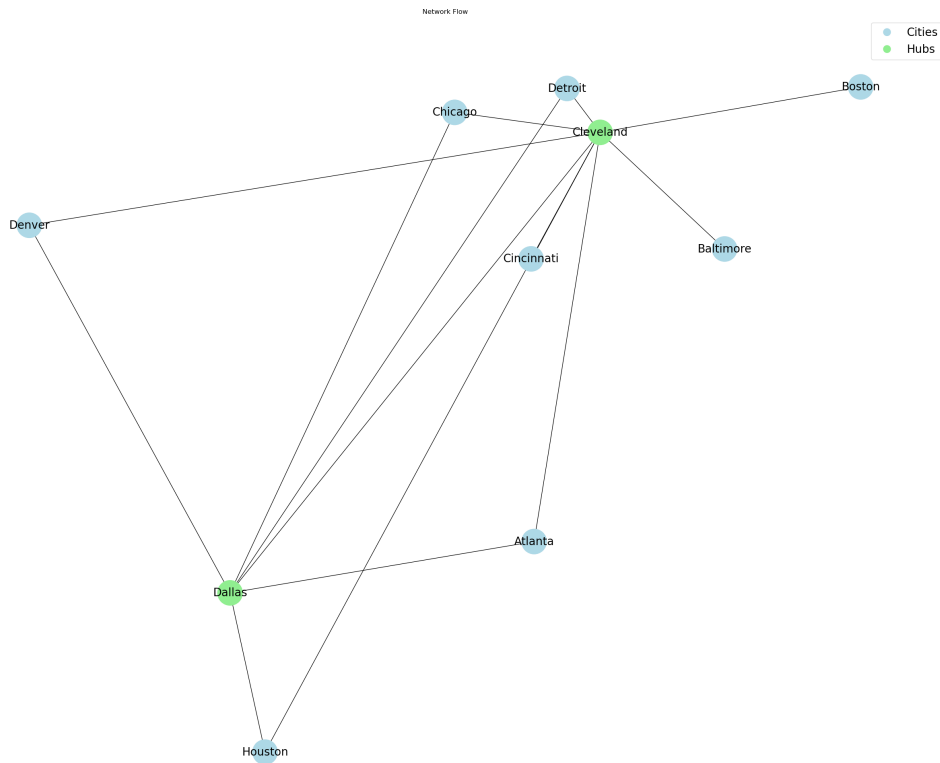


Figure 8.5: Network configuration when optimized for economic objective with passenger preferences implemented

A different hub selection is present in this network compared to the economic objective solution (S1), instead of Detroit, Cleveland is chosen as a hub. As shown in Figure 8.5, fewer connections are necessary for this optimal network. This can be linked to having more flights in a day to accommodate the time preferences, allowing demand to be met with fewer hub changes. For Baltimore, Boston and Cincinnati, a connection to only one hub is sufficient. Boston and Cincinnati have one of the least demands, and Boston is the farthest away node. Since this network design has more flights, costs are lowered by having one connection for these nodes.

Comparison of the economic objective with passenger preferences (M1) to the economic and passenger preference objective solutions (S1,S3) are given in Table 8.2, as this is a child solution of these two single objective solutions. The solution aligns with passenger preferences while showing a reduction in costs and emissions compared to the passenger preference objective solution (S3). However, this comes with an increase in costs and emissions relative to the economic objective solution (S1), which may be considered substantial by airlines.

Table 8.2: Comparison of the economic objective with passenger preferences to the single objective solutions

Attribute	Unit	Economic Objective with Passenger Preferences	Comparison to S1	Comparison to S3
Number of hubs	-	2	2	2 (predefined)
Total number of flights	-	406	12.15%	-12.50%
Total cost	Million \$	3.49	7.63%	-47.09%
Total CO_2	Kiloton	2.48	11.04%	-55.49%
Passenger Preference Deviation	-	0	-100.00%	0.00%

After this step, the environmental objective is introduced as a constraint. The minimum value of the environmental objective, 1.91 kilotons, is set as a bound with varying allowable ranges (ϵ) from 0.1 to 1.0 kilotons. The lower limit is taken as a starting point because it is found to be the lowest allowable range when optimized for the economic objective with the environmental objective as a constraint (without passenger preferences constraint). The upper limit is identified as an allowable range when both passenger and environmental objectives are set as constraints. It is observed that the model is not able to produce a solution for $\epsilon = 0.1$ kilotons and $\epsilon = 0.2$ kilotons, as this makes the constraint tight. A detailed overview of the different model outputs with varying ϵ values is given in Appendix C Table C.1, and different network designs in Figure C.1.

As the allowable range increases, the restriction on the amount of CO_2 emissions is loosened and different network designs are generated that allow for lower costs. After $\epsilon = 0.6$ kilotons, the model acts the same as when having no restrictions on the environmental constraint. The network design becomes same as the initial network without the environmental constraint when ϵ is high. As shown in Figure 8.6, lowest reduction in CO_2 can be achieved with $\epsilon = 0.3$ kilotons. However this increases the costs significantly compared to other ϵ values, and the run time is higher.

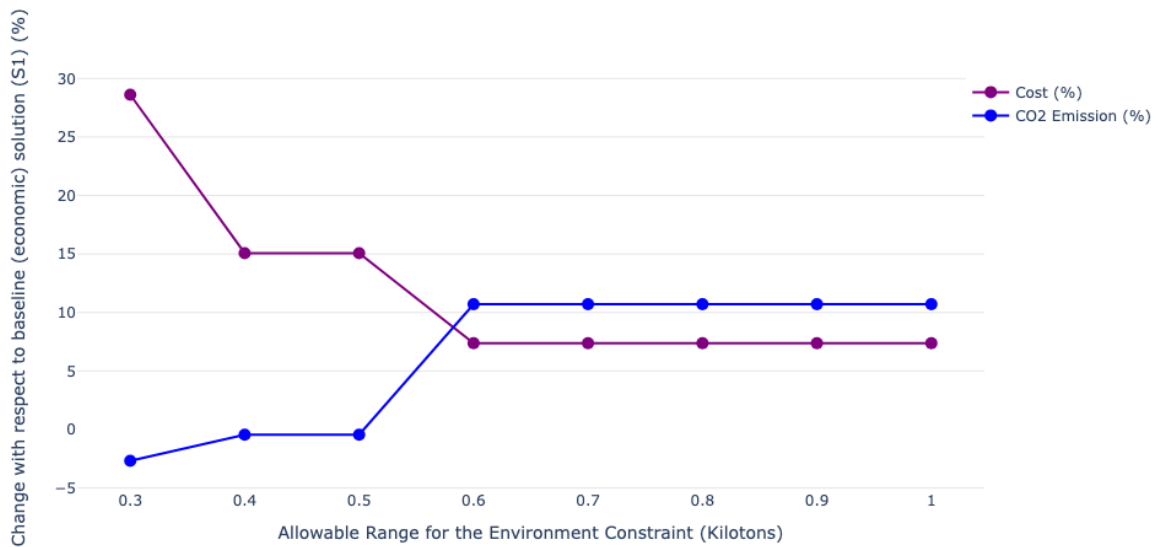


Figure 8.6: Change in cost and CO_2 emissions relative to the baseline economic objective solution (S1) for varying values of the environmental constraint, ϵ ranging from 0.3 to 1.0 kilotons ($1.91 + \epsilon$ kilotons).

8.2.2. Optimizing for Environmental Objective with Economic and Passenger Preference Constraints - M2

The model is optimized for the environmental objective with the passenger objective as a constraint (with Constraint 8.1). A comparison of this optimal solution to the parent solutions is given in Table 8.3. For accommodating passenger preferences more flights are scheduled. Similar to the economic objective combined with passenger preferences less number of connections are made with hubs per node, shown in Figure 8.7. Since more flights are going out from each node, the demand per node to different destinations can be met with fewer hub connections.

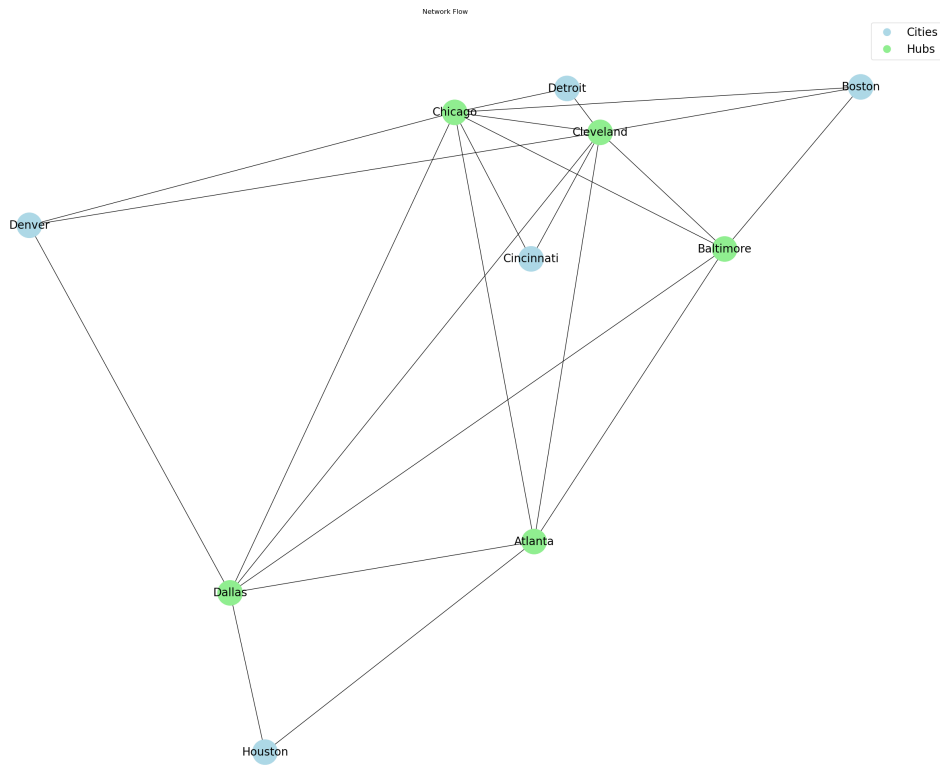


Figure 8.7: Network configuration when optimized for the environment objective with passenger preferences implemented

This solution can meet passenger preferences for departure times by reducing emissions compared to the passenger preference optimization solution (S3). When compared to the economic optimization solution (S1), emissions are decreased and costs are increased.

Table 8.3: Comparison of the environmental objective with passenger preferences to the single objective solutions

Attribute	Unit	Environmental Objective with Passenger Preferences	Comparison to S1	Comparison to S2
Number of hubs	-	7	2	2 (predefined)
Number of flights	-	328	-9.39%	-29.31%
Total cost	Million \$	4.63	42.53%	-29.94%
Total CO_2	Kiloton	2.12	-5.34%	-62.05%
Passenger Preference Deviation	-	0	-100.00%	0.00%

After this step, the economic objective is introduced as a constraint. Similar to the previous approach, the lowest possible value of the economic objective, 3.25 kilotons, and the same range of ϵ from 0.1 to 1.00 kilotons is taken into consideration when defining the constraint. Only from 0.3 kilotons feasible solutions are found. The model run time decreases as the cost constraint is loosened with increasing ϵ values, however the computational time increases significantly compared to the previous solution. Model results can be found in Appendix C Table C.2.

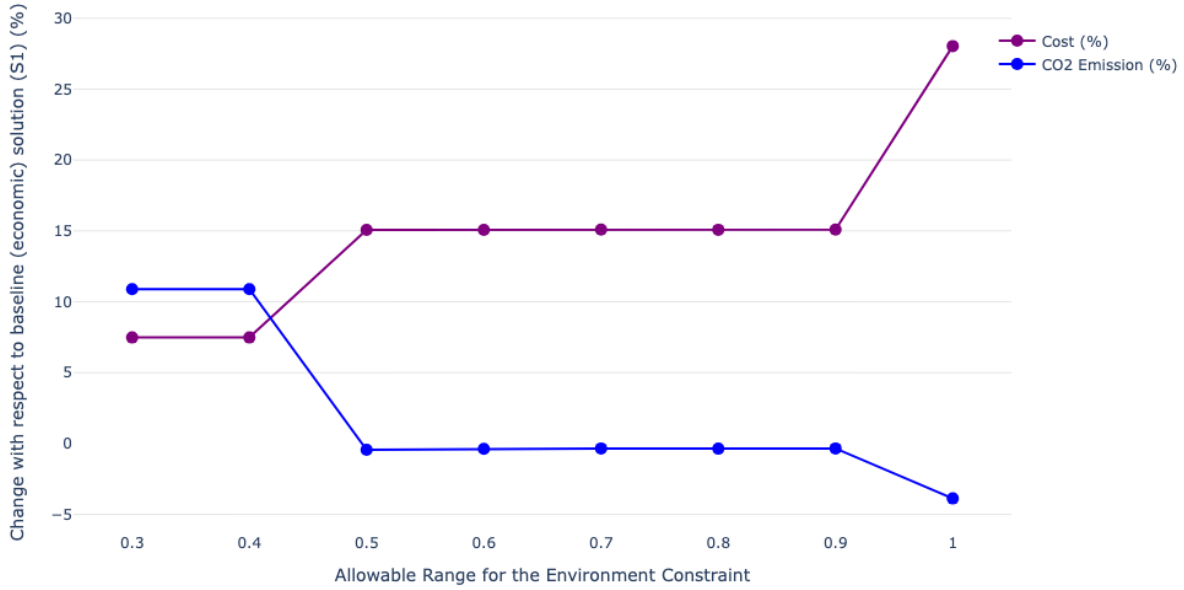


Figure 8.8: Change in cost and CO_2 emissions relative to the baseline economic objective solution (S1) for varying values of the economic constraint, ϵ ranging from 0.3 to 1.0 kilotons ($3.25 + \epsilon$ kilotons).

As shown in Figure 8.8 a decrease in CO_2 emission is possible when the economic constraint is allowed to be the highest with $\epsilon = 1.0$ kilotons, however this increases the costs. Less CO_2 emissions than the economic objective solution can be achieved, however, this increases costs. Very different network designs are generated with these optimal solutions and can be found in Appendix C. Common in these network designs are Cleveland and Dallas as hubs. With increasing ϵ values, more hubs are added, and the last network with the highest costs resembles the network without the economic constraint.

8.2.3. Optimizing for Passenger Preferences with Economic and Environmental Constraints

Various solutions are tested to optimize for passenger preferences while setting economic and environmental objectives as constraints. The lowest possible values for both objectives are used to establish the constraints, with changing allowable ranges similar to previous solutions. Even with the highest allowable range, the model's run time is significantly high. Since the minimum value for the passenger preference objective is 0, the model strives to achieve this value when optimized with other objectives as constraints. Despite the high run time, the results do not yield better optimal solutions for cost and CO_2 emissions compared to previous solutions. When $\epsilon = 1.0$ kilotons, the values for cost and CO_2 emissions are 3.91 million \$ and 2.90 kilotons, respectively. Previous optimizations have produced better results for cost and CO_2 emissions while still maintaining a deviation from passenger preferences of 0.

As this optimization does not provide satisfactory optimal solutions, it is disregarded from further analysis.

8.2.4. Multi-Objective Optimization Using Weighted Method (M3)

Another approach is taken to find balanced solutions that consider all three objectives. The weighted sum method is a common approach used in multi-objective optimization problems. The new objective function can be formulated as follows:

$$\begin{aligned}
& \sum_{j=1}^k w_j f_j(x) \\
& \text{s.t.} \quad \sum_{j=1}^k w_j = 1 \\
& w_j \geq 0, \quad j = 1, 2, \dots, k \\
& g_i(x) \leq b_i \quad i = 1, 2, \dots, m
\end{aligned} \tag{8.2}$$

The objective functions have different scales and units and therefore need to be transformed into dimensionless numbers through normalization:

$$f_j^{\text{norm}}(x) = \frac{f_j(x) - f_j^0}{f_j^0} \tag{8.3}$$

$f_j^0 = \min\{f_j(x) | g_i(x) \leq b_i, i = 1, 2, \dots, m\}$ is derived from the minimum value the objective functions can attain. These values are achieved for each objective function in their respective single objective optimization solutions (S1,S2,S3). Using this formulation Equation 8.2 can be rewritten as:

$$\begin{aligned}
& \sum_{j=1}^k w_j f_j^{\text{norm}}(x) \\
& \text{s.t.} \quad \sum_{j=1}^k w_j = 1 \\
& w_j \geq 0, \quad j = 1, 2, \dots, k \\
& g_i(x) \leq b_i \quad i = 1, 2, \dots, m
\end{aligned} \tag{8.4}$$

Using the above formulation, the combined objective function is formulated as follows:

$$\text{Min} \quad \alpha f_1^{\text{norm}} + \beta f_2^{\text{norm}} + (1 - \alpha - \beta) f_3^{\text{norm}} \tag{8.5}$$

Where f_1^{norm} corresponds to the economic objective (Equation 6.1), f_2^{norm} corresponds to the environment objective (Equation 6.3) and f_3^{norm} corresponds to the passenger objective (Equation 6.2). Different combinations of α and β values are tested to analyze different solutions. Figure 8.9 maps the impact of different weights on each objective with respect to the baseline solution (S1).

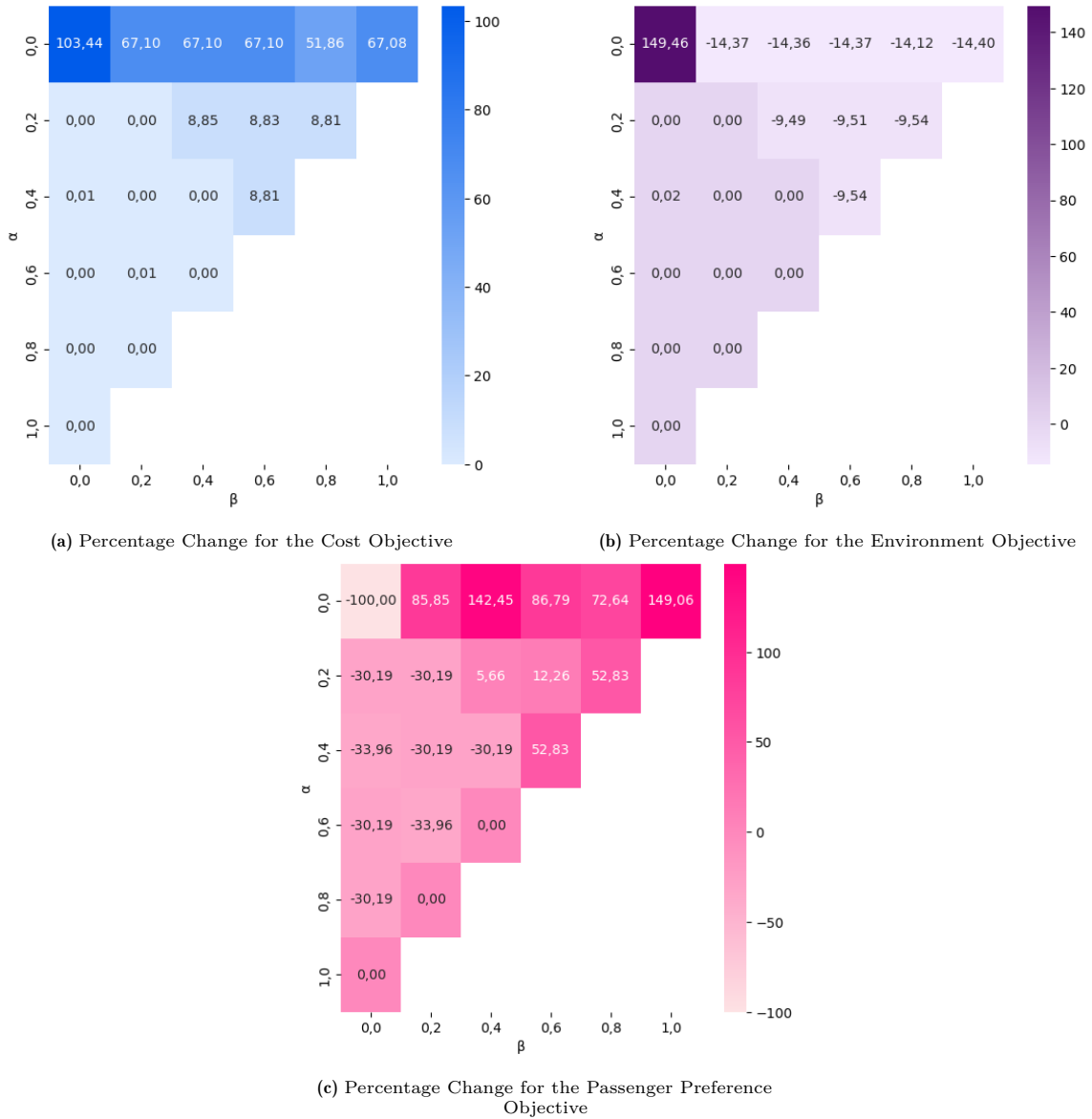


Figure 8.9: Impact of varying weights (α, β) on the objectives with respect to the baseline (economic) solution

The cost objective increases when not in consideration ($\alpha = 0$), and can increase less when the environmental objective is taken into account. Even when slightly considered, it can attain its minimum value. Costs are the highest when only passenger preferences are taken into consideration without other objectives ($\alpha = 0, \beta = 0$). This is also the case for emissions.

If cost objective is not taken into account, highest decrease in emissions are observed. However these cases increase cost significantly and do not accommodate for passenger preferences a lot. In order to have lower emissions than the baseline solution, and accommodate for passenger preferences as much as possible, the environment objective needs to have a higher weight than cost ($\beta \geq \alpha$). Since the environment objective favors more hubs in the optimal solution, these cases where the environment objective is dominant result in increased costs. Results indicate that the CO_2 emissions can be lowered up to 9,49%, in a network design that increases costs by 8,85% and the scheduled flight departure times do not deviate from the preference of passengers by 5,66%.

Deviation from passenger preferences is only minimized to 0 when it is the only objective in consideration. Without the cost objective ($\alpha = 0$) it is more difficult to accommodate for passenger preferences, since the environment objective pushes to have low number of flights. When these flights are distributed

to different time intervals, it is less likely to meet passenger preferences. With higher weight on the environment objective, passenger preferences can be met to a certain extent.

These results indicate that a network design that accommodates for passenger preferences and lowers CO_2 emissions is possible. However, these have a higher impact on costs slightly compared to the baseline solution.

8.2.5. Comparison of Different Multi-Objective Optimization Approaches

In this section, different solution approaches for the multi-objective optimization model are discussed. First approach is solving for one objective with other objectives as constraints (M1,M2), and second approach is assigning weights to objectives to create a combined objective (M3). It is shown that the deviation from passenger preferences can be minimized to 0 when solving for the economic and environmental objectives respectively, when passenger preferences are treated as a constraint. All analyses are done with respect to the baseline solution (S1). For the M1 solution, this resulted in 7.63% higher costs and 11.04% higher emissions. In this solution CO_2 emissions can be decreased when it is introduced as a constraint with $\epsilon = 0.3$ kilotons. However this impacts costs with approximately 30% increase.

For the M2 solution, passenger preferences can be fully accommodated (deviation being 0) when optimized for the environmental objective with passenger preferences as a constraint. This increases costs compared to the baseline solution with 42.53%, and is only able to decrease emissions by 5.34%. Both M1 for M2 result in the same optimal solution when $\epsilon = 1.0$ kilotons. This optimal solution is able to decrease CO_2 emissions by approximately 5% while increasing costs by approximately 30%. These solutions generate the same network design as shown in C Figure C.2. This network design is identical to the one generated in the baseline (economic) solution (S1).

When comparing approach M1 to approach M2, it should be noted that the computation time for approach M1 is faster. This is due to the complexity of the environmental objective (Equation 6.3). Apart from this, better solutions for the cost objective can be achieved with M1 while not increasing CO_2 emissions significantly. Both approaches provide optimal values where passenger preference deviation is minimized.

When objective functions are combined into a single objective with varying weights, solutions that are able to decrease CO_2 emissions are generated (M3). This is the case when the weight of the environmental objective is higher. None of these solutions fully meet passenger preferences or minimize the deviation entirely, except when the passenger preference objective is the sole focus. However, solutions can be achieved that maintain passenger preferences within acceptable limits, significantly reduce CO_2 emissions, and result in cost increases that are relatively low compared to other alternatives. An example of this is when $\alpha = 0.2$ and $\beta = 0.4$. This optimal solution can lower CO_2 emissions by 9.49% while increasing costs by 8.85% and passenger preference deviation by 5.66%.

All three approaches for multi-objective optimization (M1,M2,M3) show that network designs that lower CO_2 emissions and respect to passenger preferences of departure times increase transportation costs. First two approaches (M1,M2), where passenger preferences are introduced as a constraint provide the best solutions for the passenger preference objective. These solutions where passenger preferences are met, provide a higher trade-off between CO_2 emissions and costs. CO_2 emissions can be decreased to approximately 5% with costs increasing up to 30%. Solutions with more decrease in CO_2 emissions can be achieved with the M3 approach, approximately 10% while increasing costs by approximately 9%. In these solutions, passenger preferences are met only to a certain extent.

8.3. Sensitivity Analysis

For the sensitivity analysis, one optimal solution from each approach (M1,M2,M3) are taken into consideration. The single-objective optimization solutions (S1, S2, S3) are not included in the sensitivity analysis because they each address only one of these objectives in isolation. The primary aim of this research is to develop and assess a method that simultaneously considers and optimizes across all three objectives.

There are several parameters that could potentially impact the results of this study. However, it is

either assumed that an airline does not have a direct influence over certain parameters, or there is insufficient data available to accurately model them. Additionally, it is crucial to select a parameter for sensitivity analysis that affects all three objectives of the study.

Among the parameters that can be controlled by an airline, the choice of aircraft type stands out. This choice influences the flight cost per unit distance, emission levels, and seat capacity. Of these factors, seat capacity is particularly significant because it directly impacts all three objectives. It determines the total number of flights required to meet passenger demand. Since the number of flights is a critical variable in optimizing for economic cost, environmental impact, and passenger preferences, variations in seat capacity can lead to significant changes in the outcomes across all objectives. Specifically, a lower seat capacity might necessitate more flights to accommodate the same number of passengers, which could result in higher operational costs, increased emissions, and greater complexity in optimizing passenger preferences.

The deviation of the objective function values with respect to the baseline solution is given in Table 8.4. These solutions are the best of each approach, considering all three objectives and a decrease in CO_2 emissions. The sensitivity analysis aims to test out these scenarios when a different aircraft type is used. The sensitivity of cost and CO_2 emission values are tested for different seat capacities of an aircraft. Even though a different aircraft type would have different emission values, due to availability of data these are kept constant.

Table 8.4: Chosen optimal solutions from each approach for the sensitivity analysis

Approach	Cost objective	Environment objective	Passenger preference objective
M1	15.24%	-0.31%	0%
M2	28.19%	-3.89%	0%
M3	8.85%	-9.49%	5.66%

8.3.1. Sensitivity to Seat Capacity of Aircraft

In this analysis different aircraft capacities are tested for each chosen optimal solution. The aim is to investigate if a different aircraft type could find better optimal solutions. Other characteristics of the aircraft are kept constant due to lack of data, and only the seat capacity numbers are adjusted.

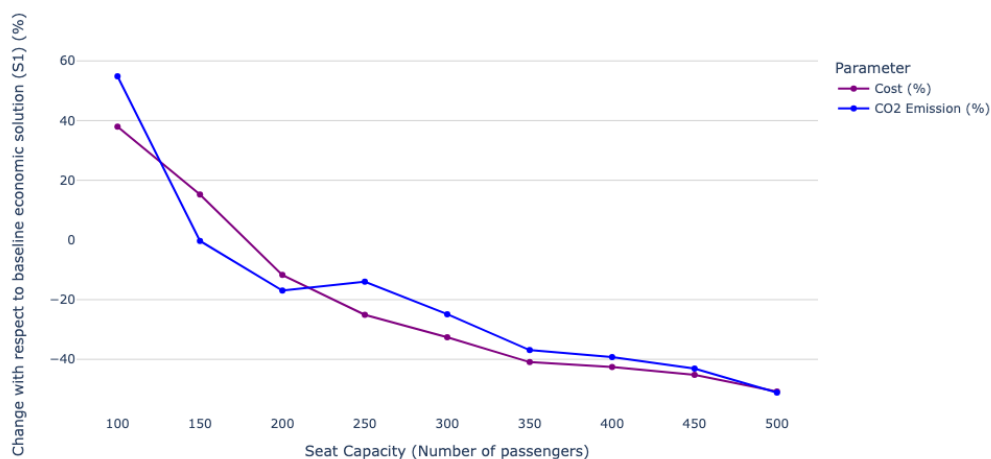


Figure 8.10: Impact of seat capacity (number of passengers) of aircraft on cost and CO_2 emissions with respect to the baseline solution for optimal solution from M1

Figure 8.10 illustrates the impact of seat capacity (number of passengers) of aircraft on the cost and CO_2 emissions, with respect to baseline solution for optimal solution from M1 approach. Having an aircraft with a lower seat number has an impact on increasing the cost and CO_2 emissions, since more aircraft are required to meet the demand. Decrease is more pronounced at lower seat capacities and tends to stabilize as seat capacity approaches 500 passengers. At lower seat capacities, reduction in cost is higher as seat capacity increases. Similar to cost, CO_2 emissions decrease significantly with increasing seat capacity, particularly between 100 and 200 passengers. Beyond this point, both reductions in cost and CO_2 continue but at a slower rate, stabilizing around 400 passengers.

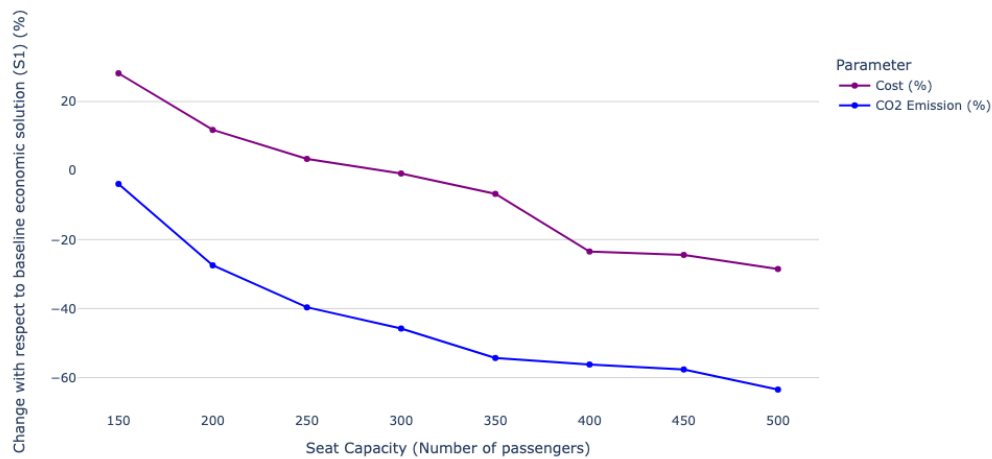


Figure 8.11: Impact of seat capacity (number of passengers) of aircraft on cost and CO_2 emissions with respect to the baseline solution for optimal solution coming from M2

Figure 8.11 presents the sensitivity analysis of the impact of seat capacity (number of passengers) of aircraft on cost and CO_2 emissions, with respect to the baseline solution for the optimal solution from M2. For this optimal solution, an aircraft with 100 seats is found to be infeasible and disregarded from the analysis. For both cost and CO_2 there is a reduction with increasing seat capacity. At lower seat capacities (150-200), reduction in costs are higher as seat capacity increases. CO_2 emission also decreases with increasing seat capacity, stabilizing beyond 350 passengers. Around 200 seats, costs are similar to the baseline solution while a significant reduction in CO_2 emissions is possible. In comparison to the M1 optimal solution, reductions for cost are more moderate for M2. However, higher reductions for CO_2 can be achieved.

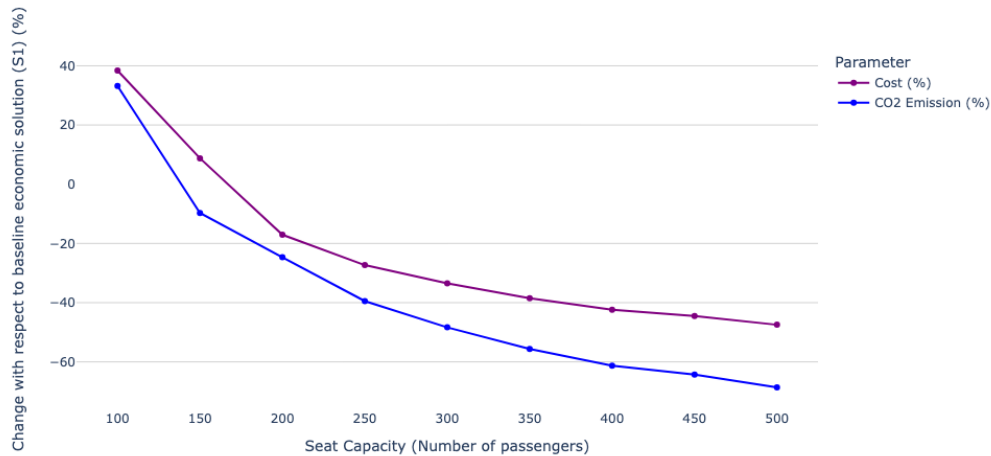


Figure 8.12: Impact of seat capacity (number of passengers) of aircraft on cost and CO_2 emissions with respect to the baseline solution for optimal solution from M3

Figure 8.12 presents the sensitivity analysis of the impact of seat capacity (number of passengers) of aircraft on cost and CO_2 emissions with respect to the baseline solution for the optimal solution from M3. A similar relationship to the M1 solution between cost and CO_2 reductions is observed, as they both decrease in a similar rate. At lower seat capacities (100-150 passengers), there is a noticeable reduction in cost as seat capacity increases. Similar to cost, CO_2 emissions decrease significantly with increasing seat capacity, particularly between 100 and 200 passengers. Beyond this point for both, the reduction continues at a consistent rate, showing further improvements up to 500 passengers.

All three solutions (derived from M1, M2, and M3 respectively) show that increasing seat capacity results in lower costs and CO_2 emissions, with the most significant reductions occurring at lower capacities. For M1 and M2, the reductions stabilize around 300-400 passengers, whereas for M3, the reductions continue steadily up to 500 passengers, suggesting a wider range of benefits for higher capacities in the M3 solution. The optimal seat capacity range for all solutions seems to be around 300-400 passengers. However, M3 shows potential benefits even at higher capacities (450-500 passengers), suggesting that larger aircraft could still provide economic and environmental advantages.

9

Discussion & Conclusion

This chapter provides a conclusion to the research. It begins with a discussion on the results of the multi-objective optimization model. The practical implications of the research are then explored, focusing on their impact on airline network design and offering policy and strategic recommendations for the aviation sector. This is followed by an examination of the research limitations and suggestions for future research directions. Finally, the chapter concludes with a summary of the research findings.

9.1. Discussion of Results

In this section, a discussion of the results of the optimization model is presented. The airline network is optimized using two types of approaches. The first approach considers the cases in which the airline network is optimized solely for one objective, and other objective functions are calculated afterward. The multi-objective optimization approach considers two different techniques to combine the multi-objectives, to find an optimal solution that can meet all the objectives. The best optimal solutions from these approaches are analyzed for their sensitivity to aircraft capacity. By analyzing both single and multiple objective solutions, this discussion provides a comprehensive understanding of how different optimization strategies affect airline network design.

9.1.1. Cost Optimization

The single objective optimization for the cost objective (S1) revealed that cost can be lowered compared to other single objective optimization solutions (S2,S3). S1 is used as the baseline solution to compare the changes in other objectives when a different optimization strategy is employed. Given that not including the passenger preference objective in the optimization results in the scheduling of flights for a day, an extra step is taken to assess how well this objective performs in terms of the deviation from the passenger preferences of departure times.

When optimized solely for the passenger preference objective (S3), costs are increased, by around 100%. However, this increase is less drastic for the optimal solutions of M1 approach. In this multi-objective approach, passenger preference deviation is minimized to its lowest level with increasing costs by 11.04% compared to the baseline solution. This demonstrates that integrating passenger preferences for departure times into the network design process has an impact on transportation costs. A balanced approach that considers both objectives has less impact on costs.

When optimized solely for the environmental objective (S2), costs increase by 67.08%. The trade-off between cost and environmental impact is significant, as in every solution, a decrease in emissions comes with an increase in costs. To achieve higher levels of decrease in emissions, costs are increased substantially. Optimal solutions of this model increase costs less either have a lower reduction in CO_2 emissions (M1 approach) or cannot fully accommodate the passenger preferences (M3 approach). However, meeting passenger preferences can help mitigate the impact of high costs. By offering schedules and routes that align with passenger preferences, airlines can attract more passengers, thereby generating more revenue. This increased revenue can offset the higher costs associated with environmentally

optimized operations.

It should be noted that the costs considered in this model are solely based on the distance the aircraft travels. However, the cost landscape of airline network planning is more complex. Factors such as fuel prices, maintenance, crew costs, airport fees, and opportunity costs also play significant roles and are not included in this analysis.

9.1.2. Environmental Effect

As highlighted in Chapter 3, the environmental concerns of the aviation industry are growing rapidly. Airlines are incentivized to consider environmentally sustainable operations, and this study aims to provide a method for the reconsideration of their network design to minimize their climate impact..

The environmental objective optimization (S2) highlighted the highest possible decrease in CO_2 emissions that can be achieved if the network is optimized solely for the environmental objective. When passenger preferences are integrated with the environmental objective (M2 approach), the decrease in emissions is less however still possible. This demonstrates that it is possible to achieve environmental benefits while also accommodating passenger preferences to some extent.

However, it should be noted that accommodating passenger preferences in the model to minimize the deviation of scheduled delays always results in scheduling more flights. Optimal solutions where this deviation is minimized have a higher total number of flights because the demand is distributed across three time intervals, causing some aircraft to travel under capacity. This underutilization of aircraft is not an environmentally sustainable practice as it leads to higher emissions per passenger and inefficient use of resources. Despite this, airlines must consider passenger satisfaction and cost minimization, making these factors essential in the network design process. This study shows a method for incorporating passenger preferences while still achieving emissions reductions, which is a better approach than not considering these factors at all. By offering routes and schedules that align with passenger preferences within a more environmentally friendly network, airlines can attract more passengers and reduce their emissions.

9.1.3. Meeting Passenger Preferences

Meeting passenger preferences for departure times is possible, however this affects costs (M1 approach) and CO_2 emissions (M2 approach). When passenger preferences are not taken into account, flights are scheduled for a day. For analyzing passenger preferences in approaches where it is not considered (S1, S2), an extra analysis is made to distribute these flights to time intervals of morning, afternoon, and evening according to the passenger preferences.

Given that the environmental solution (S2) aimed at having the least number of flights through more connections in the network, it scores less on passenger preference compared to the economic solution (S1). Introducing passenger preferences results in increased costs and CO_2 emissions. Fully accommodating for passenger preferences does allow for a decrease in CO_2 emissions in multi-objective approaches (M1,M2,M3). When some deviation from passenger preferences is allowed, better results for CO_2 emissions are achieved.

It should be noted, however, that the model only incorporated one type of passenger preference: departure times. As discussed in Chapter 4, passengers exhibit preferences on various aspects of an airline itinerary, such as departure times, travel routes and times, and cost considerations.

The model is better at accommodating passenger preferences for departure times with the economic objective optimization (M1), where the optimal solution has only two hubs. On the other hand, the environmental objective optimization (M2) features seven hubs and more direct connections. As noted in Chapter 4, passengers prefer routes with the fewest connections. While the network design for the environmental solution is better at accommodating this preference, it is less effective at accommodating preferred departure times. This indicates a trade-off between minimizing connections and optimizing departure times. Therefore, while the environmental objective optimization aligns better with passenger preferences for fewer connections, the economic objective optimization is more aligned with their departure time preferences.

When the model is solely optimized for the passenger preference objective (M3), it only considers the

deviation in flight times, without an optimal way to determine the number of hubs. This approach has many optimal solutions that could minimize the deviation, each with different network configurations. In reality, passengers likely exhibit varying preferences for hubs and may prefer network configurations that result in fewer stopovers. If these additional preferences are incorporated into the objective function, the passenger preference network could provide more comprehensive insights. Incorporating preferences for fewer connections, preferred hubs, and other itinerary aspects would likely result in a network design that better meets passenger needs and expectations. A network optimization that incorporates more of the passenger preference aspects could produce different results.

9.1.4. Different Network Designs

Different network designs are generated with different optimization approaches. In the economic objective optimization (S1), a network design featuring two hubs at the network's extremities is created. This selection is based on achieving maximum coverage with minimal distance traveled. In contrast, the environmental objective optimization results in a completely different network configuration. Given that the emission calculation method used in this study depends on the distance traveled, network designs that incorporate environmental objectives (both in single-objective and multi-objective approaches) increase the total number of connections by incorporating more hubs. This approach allows for more direct routes and fewer one or two-stop routes, thereby minimizing the distance traveled for passengers between origin-destination pairs.

When passenger preferences are considered solely, various network designs are generated that could achieve the optimal value. As a result, the hubs defined in the economic objective optimization (S1) are used, but the network generated with these hubs differed from the one in the economic solution, connecting most cities to a single hub. Given that distance is not considered, this configuration is based solely on capacity restrictions, resulting in some cities being connected to distant hubs. This approach is not cost-optimal, leading to higher costs compared to the baseline solution. When optimizing for the economic objective while incorporating passenger preferences, a more cost efficient network configuration was achieved. This results in fewer connections compared to the purely economic network, but with nodes assigned to more optimal hubs. This balanced approach provides a better overall network design by considering both cost and passenger preferences.

When the environmental constraint is introduced with a tight allowable range in the M1 approach, the network configuration begins to resemble the one from the environmental solution. CO_2 emissions are reduced, and costs are increased. As the allowable range is loosened, the network configuration gradually converges to the configuration without the environmental objective. This was also the case for M2 approach, the end network with the highest allowable range converges to the configuration without the economic objective.

9.2. Societal & Scientific Relevance

9.2.1. Societal Relevance

An analysis on societal relevance embodies measuring the social, environmental and economic return of research. It reflects the connection between scientific research and the broader community, highlighting how research influences public issues and policy making [90]. This research aims to explore a method that considers transportation costs, climate impact and passenger preferences of departure times for the optimization of airline network design. Therefore it encompasses social, environmental and economic implications connected to airline network design.

Social Implications

The social implications of this study are significant, as optimizing airline network design with considerations for economic, environmental and passenger preference of departure times can directly impact the quality of service and accessibility for passengers. By integrating passenger preferences into network design, the method proposed in this research could lead to more passenger-centric schedules, reducing travel inconveniences and enhancing overall customer satisfaction. Moreover, the environmental considerations embedded in the model highlight the potential for airlines to contribute to broader societal goals, such as reducing carbon emissions and mitigating climate change, which has direct influence on public health and global sustainability. The research aims to underscore the importance of align-

ing airline operations with both societal expectations and environmental responsibilities, potentially influencing policy-making and regulatory frameworks in the aviation industry.

Environmental Implications

The implementation of a holistic approach that takes into account cost, environment and passenger preference considerations could facilitate the transition towards sustainable air transport systems. At the core of this research is the integration of environmental objectives into traditionally economically-driven domain of airline network design. By introducing a method that explicitly incorporates CO_2 emissions as a critical component of network optimization, this study challenges the status quo and offers a paradigm shift towards environmentally responsible aviation practices. With different network designs, one of the key implications is the potential for significant reductions in greenhouse gas emissions, which are crucial in mitigating the climate impact of aviation. This is particularly important given that the aviation industry is responsible for a notable percentage of global CO_2 emissions, a figure that is expected to rise significantly in the near future.

The research highlights the complex trade-offs involved in balancing economic and environmental goals. With the utilized dataset, the model shows that while it is possible to design airline networks that are both cost-effective and environmentally sustainable, achieving this balance requires careful consideration of multiple factors such as flight frequency, route efficiency and strategic placement of hubs. Although the study primarily focuses on minimizing CO_2 emissions as an environmental objective, the implications suggest that optimizing these network parameters can contribute to more sustainable airline operations. While other factors like fuel efficiency and noise pollution were not directly analysed, the approach lays the groundwork for integrating additional environmental considerations into future network design strategies.

Economic Implications

The economic implications of this study are deeply intertwined with the potential for airlines to achieve cost efficiencies while adapting to increasingly stringent environmental regulations. By developing a method that optimizes airline network design through simultaneous consideration of economic, environmental and passenger satisfaction objectives, this research offers a comprehensive framework that can guide airlines in their decision making for operational efficiency and profitability.

The study offers insights into how economic objectives can be balanced with environmental considerations. By integrating these considerations into network design process, airlines can potentially reduce costs associated with regulatory compliance, such as emission-related fees or penalties, while maintaining cost-effective operations. In an era where airlines are under increasing pressure to reduce their carbon footprints, the ability to integrate cost and environmental goals into network design is a competitive advantage.

The study also has implications for pricing strategies and revenue management of airlines. By aligning network design with passenger preferences, particularly in terms of departure times, airlines can potentially enhance their customer satisfaction and loyalty, leading to increased demand and higher revenues. This customer-centric approach, when integrated into network design, ensures that airline's service offerings are better aligned with market demand, allowing for more effective pricing strategies.

9.2.2. Scientific Relevance

The scientific relevance of this study lies in its contribution to the field of airline network design by developing a method that integrates economic, environmental and passenger satisfaction objectives. This research addresses a significant gap in existing literature, where traditional models often focus on optimizing cost objectives alone or consider either environmental impact or passenger preferences, but rarely integrate all three objectives simultaneously. By introducing a method that simultaneously considers multiple objectives, this study advances the theoretical understanding of how complex, interrelated factors can be effectively incorporated into airline network design. The model provides a robust framework for exploring the trade-offs between different objectives, offering insights into how airlines can achieve a balance between economic efficiency, environmental sustainability, and customer satisfaction. In addition, this research lays the groundwork for future studies that could build on the proposed framework by incorporating additional factors, such as dynamic demand modeling, varying aircraft types, or real-time operational constraints. The methodological advancements presented in this

study have the potential to influence not only academic research but also practical applications in the airline industry, contributing to more sustainable and efficient network design strategies.

9.3. Limitations

The methodology employed and the assumptions made in this study bring certain limitations that should be acknowledged. These limitations may impact the generalizability and applicability of the findings. Understanding these constraints is crucial for interpreting the results accurately and for guiding future research directions.

It is important to note that only one type of climate mitigation strategy, operational improvements was considered in this study. NLR [25] highlights two other research directions as explained in Chapter 3. These are sustainable energy resources and advancement, and novel aircraft design and aircraft performance improvements. Consideration of these aspects on the network design can also provide valuable insights that can lower the climate impact of aviation.

The first limitation arises from the attempt to model a real-world scenario using a simplified model. While the model aims to capture the essential aspects of airline network design, it inevitably abstracts and simplifies many complexities of the real world. Many assumptions and simplifications are made. Additionally, the model's assumptions about passenger preferences, cost structures, and environmental impacts may not precisely reflect real-world conditions, leading to potential discrepancies between the model's predictions and actual outcomes.

First of all, the cost factor only includes the cost per mile traveled by an aircraft and an arbitrary opening cost assigned to hubs. In reality, costs concerning an airline network are more complex, involving many interrelated factors. These include but are not limited to fuel prices, airport fees and the costs related to delays and cancellations. The simplification of these cost factors can lead to an incomplete understanding of the true economic implications of different network designs.

The environmental factor only considers CO_2 emissions, and other greenhouse gases and pollutants that can have an impact on the aviation climate impact are disregarded. Other emissions such as nitrogen oxides (NO_x), water vapor, and particulates also contribute to climate change and should be accounted for in a comprehensive environmental assessment. The exclusion of these factors may lead to an underestimation of the true environmental impact of different network designs.

The passenger preference factor in this study only considers the preferred departure times of passengers. In reality, airline passengers exhibit a wide variety of preferences. Besides departure times, passengers also have preferences regarding travel routes, travel times, and costs. These factors are disregarded in this research. Incorporating a broader range of passenger preferences could lead to different outcomes and provide a more holistic understanding of how passenger behavior influences airline network design.

The availability of data is another important limitation of this research. Since network and demand data of airlines are not publicly available, this study uses passenger data from the 1970s, which has been utilized by many researchers. Consequently, the demand data is constant and likely not applicable to the current time. Since the 1970s there has been significant changes in the airline industry, which impact the relevance of using historical data for current network design studies. The limitations imposed by the reliance on passenger data from the 1970s introduce significant constraints on the contemporary relevance and applicability of this study's findings. Since the 1970s, the airline industry has undergone transformative shifts, including the exponential growth in air travel demand, driven by globalization and the proliferation of low-cost carriers. These developments have fundamentally altered passenger flow dynamics, making the static, lower-volume demand data from the 1970s an inadequate representation of the complexities and scale of modern air travel. The study's geographical limitation to U.S. cities further narrows its scope, overlooking the complexities of international operations and the varying regulatory and market conditions that shape global airline networks today.

9.4. Future Research Directions

There are several opportunities identified to build on this study. One future research direction is to enhance the existing model by incorporating real-time data and accounting for unpredictable factors that characterize the volatile aviation sector. While the current model is robust, applying it to more

up-to-date data would allow for greater relevance and accuracy in today's context. To achieve this, machine learning algorithms could be employed to predict and adapt to dynamic changes in critical factors such as passenger demand, fuel prices, and operational disruptions (e.g., weather events or air traffic delays). These factors are inherently stochastic, and incorporating them into the model through stochastic modeling techniques would allow for a more realistic and resilient airline network design. By predicting fluctuations in these variables and adapting the network configuration accordingly, the model would become more responsive to real-world conditions, enhancing its practical applicability and robustness in decision-making.

Another direction for potential research would be to integrate a more comprehensive set of variables for all objectives in consideration. For costs this could include fuel prices, maintenance costs, crew salaries, airport feed, hub costs etc. These additional costs can provide a more accurate economic analysis. Future research should also incorporate a broader range of environmental metrics, which can help to assess the environmental impact of airline operations.

Future research should consider additional passenger preferences to better align network planning with actual passenger needs and expectations. More sophisticated techniques to model passenger preferences can be implemented. Surveys and data analysis techniques could be used to gather and analyze passenger preferences, providing insights backed up by data into how different factors influence travel decisions instead of assumptions used in this study.

Another important aspect to consider is to obtain more recent and comprehensive data on airline passenger behaviour and demand. Collaborating with airlines and industry stakeholders to access current data could significantly improve the model. As the model only considers one type of aircraft, the inclusion of different types of aircraft in the modeling process could be beneficial and can provide better insights for airlines. Additionally, expanding the geographical scope to include international routes would provide a more global perspective on airline network design.

9.5. Conclusion

The aviation industry faces significant environmental challenges and regulatory pressures due to its substantial contribution to greenhouse gas emissions. Aligning with the UNFCCC principles, the industry must adopt eco-conscious strategies to reduce both CO_2 and *non* - CO_2 emissions. Currently, aviation is responsible for 2.4% of global CO_2 emissions and 3% of the EU's greenhouse emissions, with these figures expected to rise dramatically if current trends continue.

The rapid growth of the aviation sector, with an annual increase of 4.5%-5%, outpaces other modes of transport, necessitating strict environmental regulations. Governments and aviation authorities have implemented measures to curb emissions, however such measures have faced opposition due to potential inefficiencies and adverse impacts on network operations. To navigate these challenges, airlines must explore alternative strategies, including redesigning their networks with a focus on minimizing climate impacts.

Traditional network design focuses on minimizing costs driven by market demand, involving flight selection, frequency, timetables, and passenger routing. Despite advances in green aviation, most models prioritize economic targets, neglecting environmental impacts. On the other hand, network planning decisions are based on passenger demand and preferences, such as preferred travel times and route choices. A comprehensive model that integrates economic, environmental, and passenger preferences is currently absent in the literature. Taking into consideration this research gap, the following research question is generated:

How can airline network design be cost-optimized with respect to climate impacts and passenger preferences?

To address this research question, a mixed-method approach is employed. The study aims to develop a method that incorporates cost, environmental, and passenger preference considerations into the airline network design process. The research begins with an exploration of environmental considerations, followed by an investigation of passenger preferences, which together provide the criteria for selecting a suitable model for optimizing an airline's hub-and-spoke network.

The environmental considerations in airline network design are explored through a comprehensive literature review, analyzing the environmental effects of aviation and various climate mitigation strategies. This review informs the integration of environmental objectives into the airline network design, with the European Environmental Agency (EEA) methodology selected to calculate CO_2 emissions from aircraft operations, dependent on aircraft type.

Subsequently, the study examines different passenger preferences in airline network design, focusing specifically on departure times due to their impact on strategic network planning. It is revealed that passenger service quality can be assessed by the cost incurred due to travel time and schedule delay. Schedule delay is selected as the passenger preference consideration of this research.

The insights from environmental and passenger preference considerations are used to evaluate the applicability of existing hub location problems to airline network design. It is determined that the decision variables in current models are inadequate for measuring environmental impacts and passenger preferences for departure times, as they fail to account for the number of flights on each route. Consequently, the study adapts the Uncapacitated Hub Location Problem to develop a Mixed-Integer Programming (MIP) model that integrates these considerations. The model includes three objective functions aimed at minimizing costs, CO_2 emissions, and deviations from passenger preference departure times, enabling optimal decisions on network design, flight frequency, and flight schedules.

This study presents a comprehensive method that considers transportation costs, environmental impacts, and passenger preferences for departure times. The method is validated using a well-known dataset in hub location research, with the optimization problem solved through both single-objective and multi-objective approaches.

This study highlights the necessity of adopting a multi-faceted approach to airline network design that integrates economic efficiency, environmental sustainability, and passenger preferences. By applying a model that balances these three critical objectives, airlines can navigate the complexities of modern aviation more effectively. The research demonstrates that while optimizing for a single objective may yield benefits in one area, a comprehensive strategy that considers all relevant factors is essential for long-term success. This approach not only enhances operational performance but also aligns with the growing regulatory and societal demands for more sustainable and passenger-focused airline operations. Through thoughtful adjustments in network design and scheduling, airlines can create networks that are both economically viable and environmentally responsible, while also meeting the evolving expectations of their passengers.

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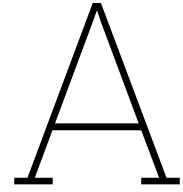
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Data used in the Model

This section provides the data used for the example case. Table A.1 shows the number of passengers traveling between each node. Table A.2 shows the distance between each node in miles. The data are taken from the CAB dataset for 10 nodes. Table A.3 gives an overview of the values for each parameter of the model. For a discussion on how they are derived, Chapter 7 can be visited.

	Atlanta	Baltimore	Boston	Chicago	Cincinnati	Cleveland	Dallas	Denver	Detroit	Houston
Atlanta	0	216	254	668	156	206	390	75	295	242
Baltimore	216	0	433	456	111	186	129	107	223	140
Boston	254	433	0	1171	199	471	198	192	553	141
Chicago	668	456	1171	0	636	1171	714	911	1711	528
Cincinnati	156	111	199	636	0	243	103	52	239	64
Cleveland	206	186	471	1171	243	0	167	117	347	118
Dallas	390	129	198	714	103	167	0	385	216	1142
Denver	75	107	192	911	52	117	385	0	187	236
Detroit	295	223	553	1711	239	347	216	187	0	148
Houston	242	140	141	528	64	118	1142	236	148	0

Table A.1: Passenger flows between cities

	Atlanta	Baltimore	Boston	Chicago	Cincinnati	Cleveland	Dallas	Denver	Detroit	Houston
Atlanta	0	576.9631	946.4954	597.5972	373.8127	559.7673	709.0215	1208.328	603.6477	695.208
Baltimore	576.9631	0	369.5327	613.0386	429.1079	312.8831	1196.489	1502.14	405.8975	1241.961
Boston	946.4954	369.5327	0	858.3308	749.6018	556.0706	1541.273	1764.791	621.3306	1603.165
Chicago	597.5972	613.0386	858.3308	0	255.0303	311.3071	790.1213	907.4331	237.0703	932.2173
Cincinnati	373.8127	429.1079	749.6018	255.0303	0	225.8954	794.1726	1080.374	238.944	879.5647
Cleveland	559.7673	312.8831	556.0706	311.3071	225.8954	0	1009.689	1216.868	94.2588	1104.574
Dallas	709.0215	1196.489	1541.273	790.1213	794.1726	1009.689	0	663.8762	982.7378	221.422
Denver	1208.328	1502.14	1764.791	907.4331	1080.374	1216.868	663.8762	0	1143.791	874.5181
Detroit	603.6477	405.8975	621.3306	237.0703	238.944	94.2588	982.7378	1143.791	0	1094.906
Houston	695.208	1241.961	1603.165	932.2173	879.5647	1104.574	221.422	874.5181	1094.906	0

Table A.2: Distance matrix between cities (in miles)

Parameters	Description
W_{ij}	See Table A.1
d_{ij}	See Table A.2
c^a	13.534 (\$/mile)
F	500000
E^{LTO}	2.57093 (kg)
R^C	2.06855 (kg)
E^C	6.51592 (kg)
p_t	1/2, 1/4, 1/4 for $t = 1$, $t = 2$, and $t = 3$ resp.
s	150 (number of seats)
C_k	See Table 7.3

Table A.3: Overview of the parameters of the model

B

Model Results for the Single-Objective Optimization

This section presents the results for the single-objective optimizations. Table B.1 shows the daily number of flights found in the optimal solution when optimized solely for the economic objective. Table B.2 shows the daily number of flights distributed among the time intervals, morning, afternoon and evening to assess how well the solution performs for the passenger preference objective. Table B.4 and Table B.3 show the daily and time interval solutions for the environment objective optimization, respectively.

Nodes / V_{ij}	Nodes										Total Seat Capacity
	Atlanta	Baltimore	Boston	Chicago	Cincinnati	Cleveland	Dallas	Denver	Detroit	Houston	
Atlanta	-	-	-	-	-	-	4	-	13	-	2550
Baltimore	-	-	-	-	-	-	2	-	12	-	2100
Boston	-	-	-	-	-	-	1	-	24	-	3750
Chicago	-	-	-	-	-	-	9	-	45	-	8100
Cincinnati	-	-	-	-	-	-	1	-	12	-	1950
Cleveland	-	-	-	-	-	-	1	-	20	-	3150
Dallas	4	2	1	9	1	1	-	6	2	16	6300
Denver	-	-	-	-	-	-	6	-	10	-	2400
Detroit	13	12	24	45	12	20	2	10	-	3	21150
Houston	-	-	-	-	-	-	16	-	3	-	2850

Table B.1: Daily flight schedule for the optimal solution of economic objective optimization (S1)

Nodes / V_{ij}	Nodes										Total Seat Capacity
	Atlanta	Baltimore	Boston	Chicago	Cincinnati	Cleveland	Dallas	Denver	Detroit	Houston	
Atlanta	-	-	-	-	-	-	Morning: 2 Afternoon: 1 Evening: 1	-	Morning: 6 Afternoon: 3 Evening: 4	-	2550
Baltimore	-	-	-	-	-	-	Morning: 1 Afternoon: 1 Evening: 0	-	Morning: 6 Afternoon: 3 Evening: 3	-	2100
Boston	-	-	-	-	-	-	Morning: 1 Afternoon: 0 Evening: 0	-	Morning: 12 Afternoon: 6 Evening: 6	-	3750
Chicago	-	-	-	-	-	-	Morning: 4 Afternoon: 2 Evening: 3	-	Morning: 22 Afternoon: 11 Evening: 12	-	8100
Cincinnati	-	-	-	-	-	-	Morning: 1 Afternoon: 0 Evening: 0	-	Morning: 6 Afternoon: 3 Evening: 3	-	1950
Cleveland	-	-	-	-	-	-	Morning: 1 Afternoon: 0 Evening: 0	-	Morning: 10 Afternoon: 5 Evening: 5	-	3150
Dallas	Morning: 2 Afternoon: 1 Evening: 1	Morning: 1 Afternoon: 1 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	Morning: 4 Afternoon: 2 Evening: 3	Morning: 1 Afternoon: 0 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	-	Morning: 3 Afternoon: 1 Evening: 2	Morning: 1 Afternoon: 1 Evening: 0	Morning: 8 Afternoon: 4 Evening: 4	6300
Denver	-	-	-	-	-	-	Morning: 3 Afternoon: 1 Evening: 2	-	Morning: 5 Afternoon: 2 Evening: 3	-	2400
Detroit	Morning: 6 Afternoon: 3 Evening: 4	Morning: 6 Afternoon: 3 Evening: 3	Morning: 12 Afternoon: 6 Evening: 6	Morning: 22 Afternoon: 11 Evening: 12	Morning: 6 Afternoon: 3 Evening: 3	Morning: 10 Afternoon: 5 Evening: 5	Morning: 1 Afternoon: 1 Evening: 0	Morning: 5 Afternoon: 2 Evening: 3	-	Morning: 2 Afternoon: 1 Evening: 0	21150
Houston	-	-	-	-	-	-	Morning: 8 Afternoon: 4 Evening: 4	-	Morning: 2 Afternoon: 1 Evening: 0	-	2850

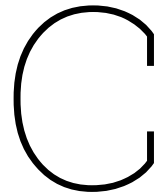
Table B.2: Daily flight schedule for the optimal solution of economic objective optimization, shown in time intervals

Nodes / V_{ij}	Nodes										Total Seat Capacity
	Atlanta	Baltimore	Boston	Chicago	Cincinnati	Cleveland	Dallas	Denver	Detroit	Houston	
Atlanta	-	2	1	5	2	2	3	-	1	2	2700
Baltimore	2	-	5	4	1	2	1	-	1	1	2700
Boston	2	5	-	9	2	7	-	-	-	-	3450
Chicago	5	4	8	-	5	8	5	10	14	4	7650
Cincinnati	2	1	2	5	-	2	1	-	3	1	2100
Cleveland	2	2	9	8	2	-	2	1	7	1	4800
Dallas	3	1	-	5	1	2	-	4	1	8	5850
Denver	-	-	-	10	-	1	3	-	-	2	2400
Detroit	-	1	-	13	3	8	2	-	-	-	3750
Houston	2	1	-	4	1	1	8	2	-	-	5700

Table B.3: Daily flight schedule for the optimal solution of the environment objective optimization (S2)

Nodes / V_j	Nodes										Total Seat Capacity
	Atlanta	Baltimore	Boston	Chicago	Cincinnati	Cleveland	Dallas	Denver	Detroit	Houston	
Atlanta	-	Morning: 1 Afternoon: 1 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	Morning: 2 Afternoon: 1 Evening: 2	Morning: 1 Afternoon: 1 Evening: 0	Morning: 1 Afternoon: 1 Evening: 0	Morning: 2 Afternoon: 1 Evening: 0	-	Morning: 1 Afternoon: 0 Evening: 0	Morning: 1 Afternoon: 1 Evening: 0	5850
Baltimore	Morning: 1 Afternoon: 1 Evening: 0	-	Morning: 2 Afternoon: 1 Evening: 2	Morning: 2 Afternoon: 1 Evening: 1	Morning: 1 Afternoon: 0 Evening: 0	Morning: 1 Afternoon: 1 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	-	Morning: 1 Afternoon: 0 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	5400
Boston	Morning: 1 Afternoon: 1 Evening: 2	Morning: 2 Afternoon: 1 Evening: 2	-	Morning: 4 Afternoon: 2 Evening: 0	Morning: 1 Afternoon: 1 Evening: 0	Morning: 3 Afternoon: 2 Evening: 2	-	-	-	-	7200
Chicago	Morning: 2 Afternoon: 1 Evening: 2	Morning: 2 Afternoon: 1 Evening: 1	Morning: 4 Afternoon: 2 Evening: 2	-	Morning: 2 Afternoon: 1 Evening: 2	Morning: 4 Afternoon: 2 Evening: 2	Morning: 2 Afternoon: 1 Evening: 2	Morning: 5 Afternoon: 2 Evening: 3	Morning: 7 Afternoon: 3 Evening: 4	Morning: 2 Afternoon: 1 Evening: 1	18000
Cincinnati	Morning: 1 Afternoon: 1 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	Morning: 1 Afternoon: 1 Evening: 0	Morning: 2 Afternoon: 1 Evening: 2	-	Morning: 1 Afternoon: 1 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	-	Morning: 2 Afternoon: 1 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	5550
Cleveland	Morning: 1 Afternoon: 1 Evening: 0	Morning: 1 Afternoon: 1 Evening: 0	Morning: 4 Afternoon: 2 Evening: 3	Morning: 4 Afternoon: 2 Evening: 2	Morning: 1 Afternoon: 0 Evening: 0	-	Morning: 1 Afternoon: 1 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	Morning: 3 Afternoon: 2 Evening: 2	Morning: 1 Afternoon: 0 Evening: 0	8400
Dallas	Morning: 2 Afternoon: 1 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	-	Morning: 2 Afternoon: 1 Evening: 2	Morning: 1 Afternoon: 0 Evening: 0	Morning: 1 Afternoon: 1 Evening: 0	-	Morning: 2 Afternoon: 1 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	Morning: 4 Afternoon: 2 Evening: 2	7200
Denver	-	-	-	Morning: 5 Afternoon: 2 Evening: 3	-	Morning: 1 Afternoon: 0 Evening: 0	Morning: 2 Afternoon: 1 Evening: 0	-	-	Morning: 1 Afternoon: 1 Evening: 0	16500
Detroit	-	Morning: 1 Afternoon: 0 Evening: 0	-	Morning: 6 Afternoon: 3 Evening: 4	Morning: 2 Afternoon: 1 Evening: 0	Morning: 4 Afternoon: 2 Evening: 2	Morning: 1 Afternoon: 1 Evening: 0	-	-	-	3750
Houston	Morning: 1 Afternoon: 1 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	-	Morning: 2 Afternoon: 1 Evening: 1	Morning: 1 Afternoon: 0 Evening: 0	Morning: 1 Afternoon: 0 Evening: 0	Morning: 4 Afternoon: 2 Evening: 2	Morning: 1 Afternoon: 1 Evening: 0	-	-	5700

Table B.4: Daily flight schedule for the optimal solution of the environment objective optimization (S2), shown in time intervals

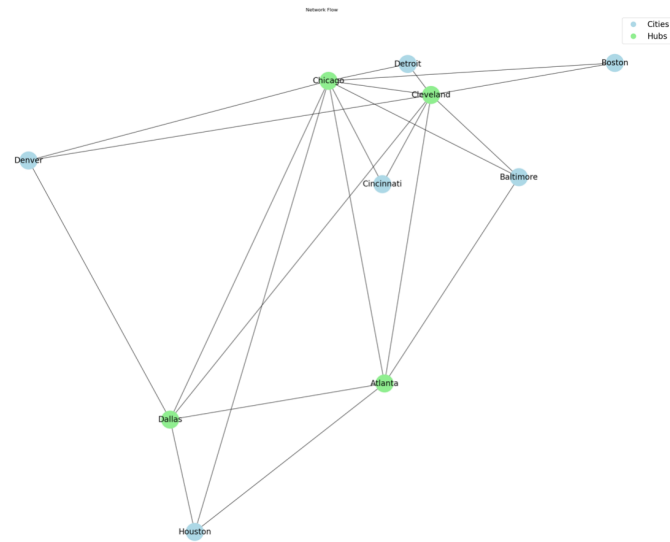


Model Results for Multi-Objective Optimization

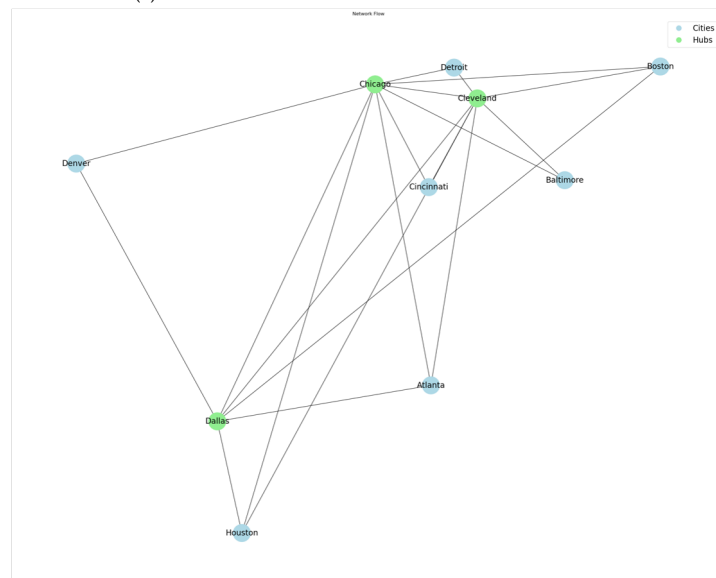
This section presents the solutions for the multi-objective optimization approach. Table C.1 shows the detailed overview for the solutions derived from approach M1 (economic objective with passenger preference and environment constraint), with varying allowable ranges for the environment constraint. Figure C.1 highlights the different network configurations derived from this approach. Table C.2 shows the detailed overview for the solutions derived from approach M2 (environment objective with passenger preference and economic constraint), with varying allowable ranges for the economic constraint. Figure C.2 highlights the different network configurations derived from this approach.

Table C.1: Detailed Overview for the Economic Objective with Passenger Preferences and varying ranges for the Environment Constraint ($1.96 + \epsilon$ kilotons)

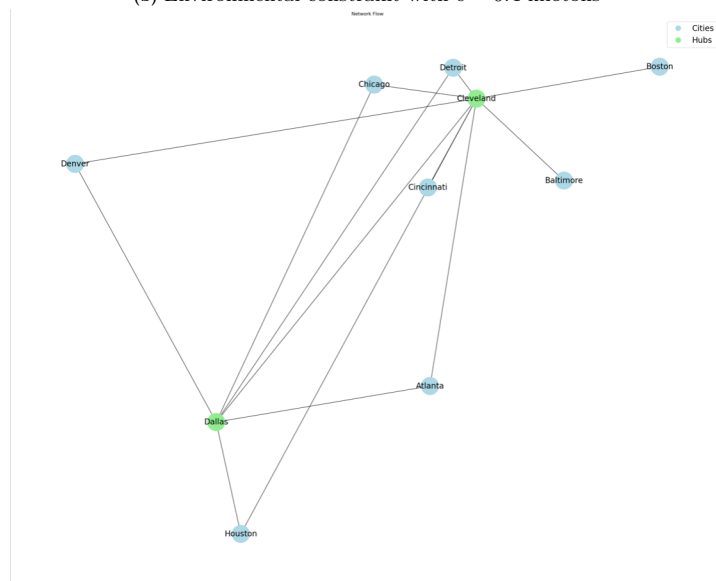
Parameter	Allowable Range , ϵ kilotons							
	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Gap (%)	0	0	0	0	0	0	0	0
Cost (Million \$)	4.18	3.74	3.74	3.49	3.49	3.49	3.49	3.49
Environment (kiloton CO ₂)	2.18	2.23	2.23	2.48	2.48	2.48	2.48	2.48
Number of flights	320	336	336	408	408	408	408	408
Hubs	Atlanta, Chicago, Cleveland, Dallas	Chicago, Cleveland, Dallas	Chicago, Cleveland, Dallas	Cleveland, Dallas	Cleveland, Dallas	Cleveland, Dallas	Cleveland, Dallas	Cleveland, Dallas



(a) Environmental constraint with $\epsilon = 0.3$ kilotons



(b) Environmental constraint with $\epsilon = 0.4$ kilotons



(c) Environmental constraint with $\epsilon = 0.6$ kilotons

Figure C.1: Network structures for Economic Objective with passenger preferences and different ϵ Values for the environmental constraint

Table C.2: Detailed Overview for the Environmental Objective with Passenger Preferences and varying ranges for the Economic Constraint ($3.25 + \epsilon$ kilotons)

Parameter	Allowable Range , ϵ kiloton							
	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Gap (%)	0	0	0	0	0	0	0	0
Cost (Million \$)	3.49	3.49	3.74	3.74	3.74	3.74	3.74	3.74
Environment (kiloton CO ₂)	2.48	2.48	2.23	2.23	2.23	2.23	2.23	2.15
Number of flights	408	408	336	336	336	336	336	320
Hubs	Cleveland, Dallas	Cleveland, Dallas	Cleveland, Dallas, Chicago	Cleveland, Dallas, Chicago	Cleveland, Dallas, Chicago	Cleveland, Dallas, Chicago	Cleveland, Dallas, Chicago	Cleveland, Dallas, Chicago, Balti- more

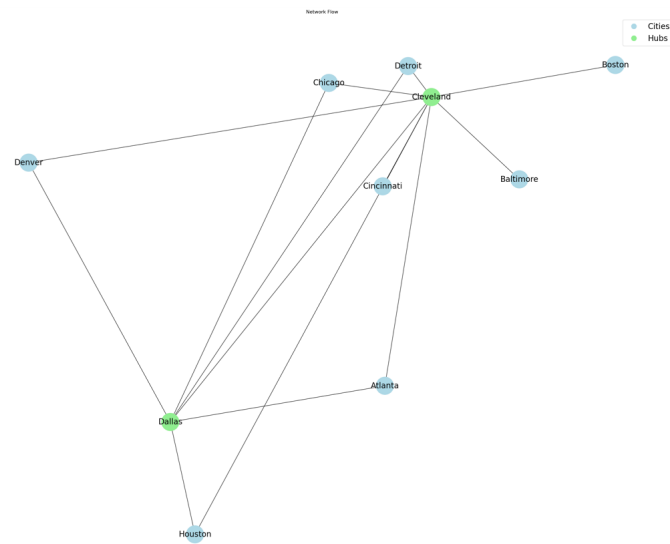
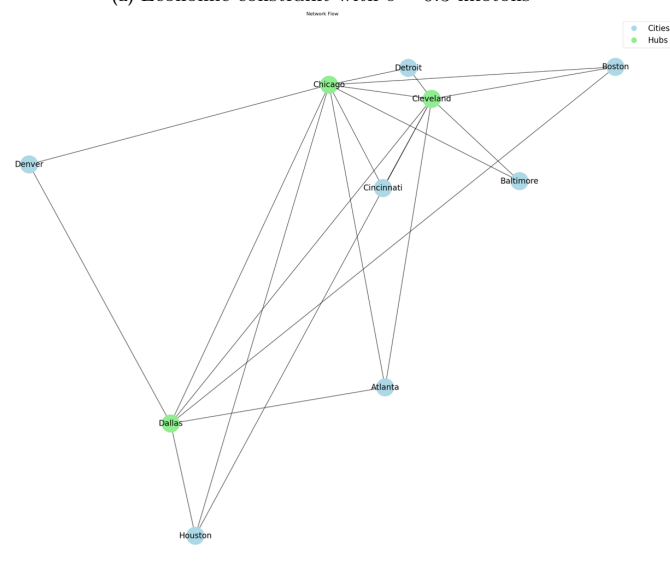
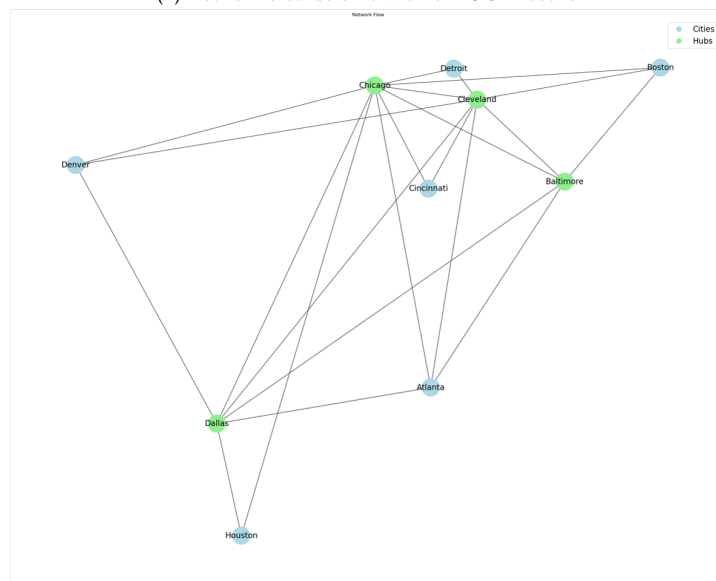
(a) Economic constraint with $\epsilon = 0.3$ kilotons(b) Economic constraint with $\epsilon = 0.5$ kilotons(c) Economic constraint with $\epsilon = 1.0$ kilotons

Figure C.2: Network structures for Environment Objective with passenger preferences and different ϵ values for the economic constraint