Assessment of Climate Impact Mitigation Potential of Intermediate Stop Operations

A Dynamic Programming Approach

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María Seoane Álvarez
Delft, August 2021

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List of Abbreviations

CH_4	Methane
CO_2	Carbon Dioxide
NO_x	Nitrogen Oxides
O_3	Ozone
RF	Radiative Forcing
SO_2	Sulfur Dioxide
ATR	Average Temperature Response
COC	Cash Operating Costs
DLR	German Aerospace Center
DP	Dynamic Programming
ETS	European Trading Scheme
ISO	Intermediate Stop Operations
MTOW	Maximum Take-off weight

Introduction

The rapid growth of the aviation industry has created the urgent need for a transition to a more sustainable practice. Aircraft manufacturers focus their research resources in developing new technology. This technology revolves around optimizing vehicle design to make them more efficient or to transition to green energy sources. The development of propulsion systems powered by green fuels presents a long term strategy to achieve sustainability goals. In addition to new technology, aviation emissions can be reduced by implementing operational improvements in the airline networks. Some of these operational improvements include flying lower and slower, trading aircraft size by flight frequency and intermediate stop operations. This research focuses on studying the viability of this last strategy. Intermediate Stop Operations (ISO) is defined as the addition of re-refuelling stops in long haul flights (see Figure 1).

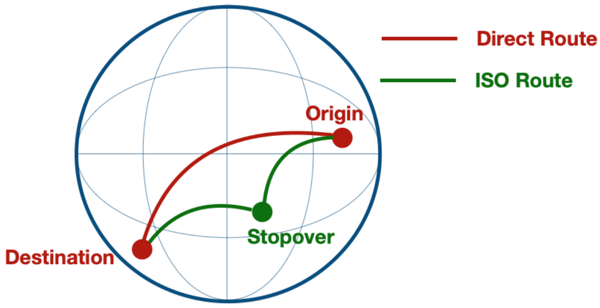

Figure 1: Direct flight vs. flight with a stopover.

Current airline planning models fail to provide an integration with climate assessment techniques. To fill this knowledge gap the following research question is proposed for this thesis:

How to effectively model multiple airline network set-ups and trajectory constraints in order to determine the climate impact of intermediate stop operations?

And derived from it, the following subquestions:

- What is the most suitable modelling framework?
- What are the relevant airline operations aspects to model?
- Which set of constraints should be included in the model?
- What are the relevant metrics to evaluate strategy impact?

This thesis is split into three parts. Part I contains the scientific paper. Part II presents the literature review, which compiles relevant information and sources for the research. Part III contains the supporting material, which provides extra information about some of the topics in the scientific paper. This extra material contains the original schedule used as input for the demand generation and the detailed schedule that results from the simulation of the base scenario. Furthermore it contains an elaboration on how demand was generated from an airline schedule and a description of the locations chosen for the stop-overs.

I

Scientific Paper

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A dynamic programming approach to studying the climate impact mitigation potential of intermediate stop operations

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Abstract

Aviation emissions present a significant contribution to climate change. The rate at which new technology is developed cannot suffice the emission reduction requirements for the growth of this industry. Therefore, new areas of improvement, such as operational changes, should be considered. The inclusion of stop-overs in long-haul routes can potentially result in a reduction of the fuel required for certain routes. This strategy is known as intermediate stop operations (ISO) and in order to test its performance, it is necessary to study economic, environmental and operational consequences. The implications of ISO are best represented with the model of an airline network. The simulation within which ISO is tested is built using a dynamic programming approach to obtain an optimal fleet assignment and network schedule. Dynamic programming allows for a division of the optimization problem into smaller subroutines, which significantly reduces computational time. Moreover, this approach allows solving the optimization problem such that the level of the activity of the airline is not directly proportional to the outcome. The case study under which the proposed methodology is tested belongs to the weekly operations of the airline Alitalia. Long haul operations are evaluated for the base scenario which imitates current operations and then compared to the introduction of a stop-over. Splitting flights into two legs results in a reduction of the fuel consumption per passenger transported of around 5% and a subsequent reduction in climate impact of 0.1%. These values are achieved compromising total flight time, however, no reduction in the profit generated per passenger is observed.

Keywords Airline Operations · Dynamic Programming · Fleet Assignment · Scheduling · Sustainability · Emissions · ClimOp

1 Introduction

Sustainability in aviation is a current pressing issue, a main research focus for the aerospace industry. The growth potential of this sector is strongly defined by its ability to reduce fuel consumption and therefore, climate impact. Global warming is the direct consequence of the radiative imbalance created in the atmosphere by the emission of pollutant compounds. Commercial aviation is the source of millions of tons of CO_2 emitted to the atmosphere every year. In addition, particulate matter arising from fuel combustion presents a serious threat to the local air quality of areas surrounding airports. Pollutant substances have different contributions for air quality deterioration and climate change. These differences associate mainly with their chemical properties and atmospheric residency times, furthermore, emission analysis is influenced by location and altitude. The future of aviation relies on both pillars, reducing emissions and designing for optimized flight routes. Dessens et al. [2014b] classify the compounds in three main categories: inevitable products of combustion, such as Carbon Dioxide (CO_2) and water vapor; products that depend on the conditions of combustion, NO_x, hydrocarbons and carbon monoxide; and lastly, those linked to fuel composition, for instance, SO_2. Upon interaction with the atmosphere, these compounds generate radiative forcing, which drives the Earth to new equilibrium temperatures. This creates what is commonly known as climate change. The different nature and properties of the emitted substances make the search for a climate change quantification variable extremely complex. The existing metrics for climate change lack clarity as the uncertainty surrounding its measurement decreases. Ultimately, the consequences of climate change, measured as damages are the most relevant for the public, however, quantifying natural disasters and other occurrences is rather unrealistic. Dessens et al. [2014b] introduce the concepts of Global Warming Potential and Global Temperature Potential, both variables failing to accurately describe the combined action of different emissions. Radiative Forcing (RF) is widely used as a reference measure, nonetheless, it fails to consider location and season of the emissions. In addition. RF is an inaccurate representation of long-term impact. Average Temperature Response (ATR) refers to the mean change of temperature in the Earth's surface over a given time horizon. ATR outperforms other indicators in combining accuracy and relevancy, it is, therefore, the main variable used to assess the climate impact of aviation. Contrary to other metrics, ATR allows to evaluate the impact of emitted substances with different residency times. The studied compounds provide different long and short-term impacts, requiring a metric that accounts for a variable interaction period.

Airlines and aircraft manufacturers direct their efforts towards developing and implementing new technologies. Green fuels and electric aviation are the two main areas of research. Unfortunately, no major breakthrough has yet been presented to the public. Regarding aircraft technology, developments relate to vehicle efficiency enhancement. However, Dahlmann et al. [2016b] state that fuel efficiency improvements do not go higher than 1-2% per year. From the legislation and regulation perspective, measures are the competence of multinational alliances. Country-level changes do not trigger the required improvements due to the international character of aviation. In the year 2005, the European Union launched the European Trading Scheme (ETS), intending to regulate the greenhouse emissions in the member countries. Unfortunately, previous research (Faber [2017]) shows that no significant environmental saving can be achieved without a decrease in demand. The ClimOp project is born as an attempt from the European Commission to implement operational improvements within the network of European airlines, and in doing so achieve a reduction in the climate impact of aviation.

The ClimOp Project

"*ClimOp will investigate, for the first time, in a sound research framework, which operational improvements do have a positive impact on climate, taking non-CO_2 effects into account. Subsequently, it will analyze and propose harmonized mitigation strategies, that foster the implementation of these operational improvements. To this end, the ClimOp consortium builds on its knowledge and expertise covering the whole spectrum from aviation operations research as well as atmospheric science and consulting to airline and airport operations.*"[1]

[1]Proposal template: ClimOp, Climate Assessment of Innovative Mitigation Strategies Towards Operational Improvements in Aviation,2019

This paper contributes to the project by providing an assessment methodology for the proposed operational improvements. Strategies should be evaluated based on economic, operational and environmental indicators. For the latter, non-CO_2 effects should be considered in addition to those of CO_2 since these represent 50% of aviation's impact. The ClimOp project aims to study mid-to-long term impact (i.e. decadal) of changes that can be readily implemented in the current flight planning. Assuming no modification of the current fleet, some of the proposed improvements include: flying lower and slower, trading aircraft size for flight frequency and the introduction of intermediate stop operations. The focus of this research is to evaluate the latter. Intermediate Stop Operations (ISO) is based on introducing a stopover in current routes (Figure 1 creating a reversed snowball effect. This means reducing the amount of 'fuel to carry fuel' that is initially loaded into the aircraft. When choosing a dynamic programming approach, it is possible to decompose airline planning into sub-problems, and therefore, analyze each of the operations separately. It is a multi-stage decision approach to creating a fleet assignment and network schedule.

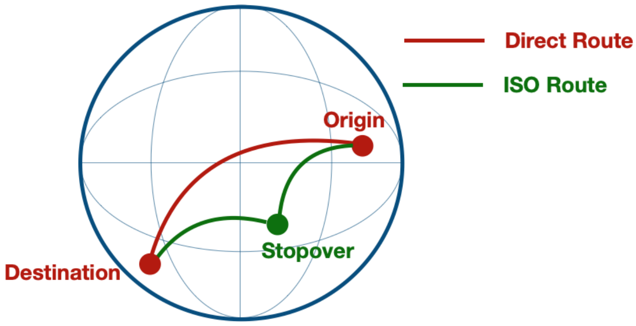

Figure 1: Original routing versus ISO routing.

Paper Contribution

The research presented in this paper merges the fields of airline planning and environmental impact assessment for aviation. In doing so it provides a tool that can be used to evaluate any current network but also those that include operational improvements. While the tool has been tested using synthetic data, there is nothing that indicates that it cannot be used to simulate and assess real networks. Four main contributions can be deducted from this work: (1) A climate impact assessment derived from a network planning model, results from the fleet assignment and schedule are fed directly into climate impact assessment, making it possible to generate network-wide or individual flight climate impact evaluation (2) An adaptable model that allows for alterations in the network and environment analysis, serving as a basis for future research ; (3) An implementation of intermediate stop operations within a time-space network, without needing to add extra nodes or complexity to the fleet assignment problem. This provides the benefit that the intermediate stops may be modified without altering the network.

Paper Structure

This paper is structured as follows. Section 2 elaborates on the relevant literature. Section 3 presents the Fleet Assignment Problem and its formulation. Section 4 presents the methodology chosen to solve the optimization of the network and elaborates on the formulation of the dynamic programming algorithm. Section 5 elaborates on the climate impact assessment methodology and Section 6 introduces the data and the conditions for the case study under which the model was tested. Section 7 presents the results of the network modeling and the climate impact assessment. Finally, Section 8 reflects on these results and provides conclusions and recommendations for future work in the field.

2 Relevant Literature

The goal of this research is to provide an assessment methodology for operational improvements. Current approaches are limited to network planning for the airline or climate impact assessment. In the field of airline planning, consecutive problems are solved to create a complete network. These problems relate to fleet planning and assignment, aircraft rotation and crew scheduling. For the study of the implementation of ISO, it is required to obtain a fleet assignment and a network schedule to study the impact on fuel consumption. Relevant literature for this problem relates to multiple fleet planning approaches and previously used climate impact assessment techniques.

2.1 Fleet Assignment Models

The fleet assignment model focuses on generating route assignments for the existing aircraft within the network. It is an optimization problem that has the goal of maximizing profit. Such models are widely used in the airline business to conduct operations planning and can be adjusted to include constraints and considerations that are airline and network specific. The inputs required for this problem relate to aircraft, demand and network characteristics. Two main approaches are commonly used for the network definition: connecting network and time-space network. For the first one, the nodes are defined by arrival and departure times. A connection arc joins two nodes, which means that an aircraft has been assigned to the connection of two flight legs. The viability of this method is limited because it requires all the potential connections to be pre-defined. On the other hand, the time-space network considers the different stations at the different time steps to be nodes. The flight legs are the decision variables, and it allows for the generation of an airline schedule.

Modern fleet assignment models are built using linear or dynamic programming. For a linear approach, all the decisions should be made upfront, while dynamic programming allows for multi-stage decision making. This means that the problem is divided into smaller routines that are evaluated separately. Hane et al. [1995] create a base mathematical formulation for a linear programming approach to the fleet assignment problem. The objective function is to minimize the total cost incurred by the flights in the network. The constraints included in this formulation ensure that the flow of aircraft is conserved at all times, this means that the generation of flights is subjected to aircraft availability. This model is used as a basis for further research in the airline planning field, such as that presented by Faber [2017]. One major drawback for the use of linear programming in this research is that it does not allow for the creation of a schedule, the resultant decision variables only present whether a certain aircraft is assigned to fly a certain route.

Intending to produce a network schedule, Hersh [1974] presents a heuristic approach to the fleet assignment problem. The four major stages introduced in this research are then used as a basis for the dynamic programming formulation:

1. Generation of feasible routes.
2. Sequential assignment of aircraft routing.
3. Passenger assignment and network evaluation.
4. Sequential reassignment of routings to achieve improved performance.

Steps 2-4 are run repeatedly until no further improvement in the network can be achieved. Woudenberg [2019] adapts this approach to individual aircraft studies, decomposing the scheduling into individual vehicles. This model is run based on aircraft availability and it relies on decisions that ensure maximum profit at the end of the planning period. One disadvantage of this approach is that previous decisions cannot be changed. This results in sub-optimal solutions when new information is made available.

2.2 Aviation Climate Impact Assessment

Dahlmann et al. [2016a] present the CATS project, developed by DLR (German Aerospace Center), to study the potential benefit of climate-optimized aircraft. This research compares the relative cash operating costs (COC) and the relative average temperature response (ATR) of high sales middle-to-long range aircraft versus its climate optimized equivalent. ATR is defined as the mean change in temperature of the Earth's surface. This research shows that an 11% reduction in ATR can be achieved with a 1% COC increase. This serves as a metric to compare climate savings potential and the costs associated with the implementation of new technology.

Furthermore, Grewe and Stenke [2008] introduce the AirClim model as a linearization of the atmospheric processes product of the environmental impact of aviation. The AirClim model does not consider historical data and uses as its inputs aircraft emission data, precalculated atmospheric data and background data on the evolution of emissions. The precalculated input data is obtained from a chemical model that studies compound perturbations in different emission regions. These different emission regions are defined such that the impact on multiple geographic locations can be studied. Each emission area is characterized by different mixing ratios which impact the interaction of emissions with the standard atmosphere. The different sources used for input in the AirClim model introduce uncertainties in the calculation. These uncertainties cannot be accurately evaluated because they arise from the multiple techniques that exist to model climate effects.

3 Problem Definition

The implementation of operational improvements within current networks requires an intensive assessment of their viability. Testing whether these measures actually result in emissions savings is crucial for their application. Moreover, other aspects such as operational and economic impact should be studied as consequences for the airline and other parties involved. ISO consists of including stops in long-haul flights to reduce total aircraft weight, and therefore, fuel consumption. The problem considered here involves the planning of solely long-haul routes. This reduces computational complexity significantly and ensures only relevant routes are studied.

Modern fleet assignment problems include the possibility of creating a network schedule. The problem outlined in this section is greatly based on that proposed by Woudenberg [2019] and Wang [2016]. This research aims to expand this previous work by making it adaptable to new operational strategies and integrating the climate assessment tool. The network is presented as a time-space network, allowing for a problem that is defined in both time and location. Given the existing demand for a certain number of routes and airline data regarding the available fleet, the goal is to design a week-long flight schedule under which certain operational improvements can be tested. The demand is defined as the number of passengers that would like to fly from A to B, assuming that connecting passenger demand is captured within these values. Note that certain considerations, such as airport characteristics, should be included in the modeling, for instance, curfews and runway length limitations. The fleet assignment problem is constructed based on profit maximization, therefore it is crucial to provide an accurate cost breakdown. For this research fuel costs are of great relevance, since the saving of fuel will translate into monetary savings, motivating the implementation of ISO.

3.1 Intermediate Stop Operations

ISOs operate under the assumption that two nodes are not directly connected by a flight arc, but rather two separate legs. For simplification purposes, this research does not recognize stop-overs as new nodes on the time-space network. If the assignment loops result in optimal allocation when a stop is included, the only changes that should be added are the extra travel time, the varying fuel load and the corresponding economical consequences. Previous research shows that there are flight distances under which the implementation of ISO is not beneficial for the network. Martinez Val et al. [2013] concludes that fuel savings are only observed when the distance between a certain city pair is between 7,000 and 10,000 km (3,800 - 5,400 NM). This research uses 7,000 km as the threshold for the ISO implementation to be triggered. This means that general results are obtained for a network in which only flights of distances higher than 7,000 km are a candidate for introducing a stop-over. Due to the assumptions used in this research, mainly related to the neglect of flight profiles, there is no minimum distance under which ISO is not applicable. However, to continue on previous research on the topic, only distances higher than the aforementioned threshold are considered.

4 Methodology: Dynamic Programming Routine

Dynamic Programming is proposed as an alternative to linear solutions for optimization problems. It is based on a problem breakdown such that every decision is based on the previous one. Linear programming is particularly useful for problems where the inputs and outputs are directly proportional to the level of activity. According to Dreyfus [1956], there are a wide variety of problems where linear programming is not applicable, due to the return of an activity being modeled as a stochastic function of the level of activity. Dynamic Programming is used for problems that can be broken down into sub-routines, for which it is possible to determine individual solutions with the available information. This approach reduces complexity and computation time significantly. Wang [2016] defines the fleet assignment problem as a dual-level problem. On the shallow level, each aircraft in the fleet is analyzed separately, such that individual optimized routing and scheduling is created for each vehicle before they are added to the network. The flow of the dynamic programming problem can be summarized as presented in Figure 2.

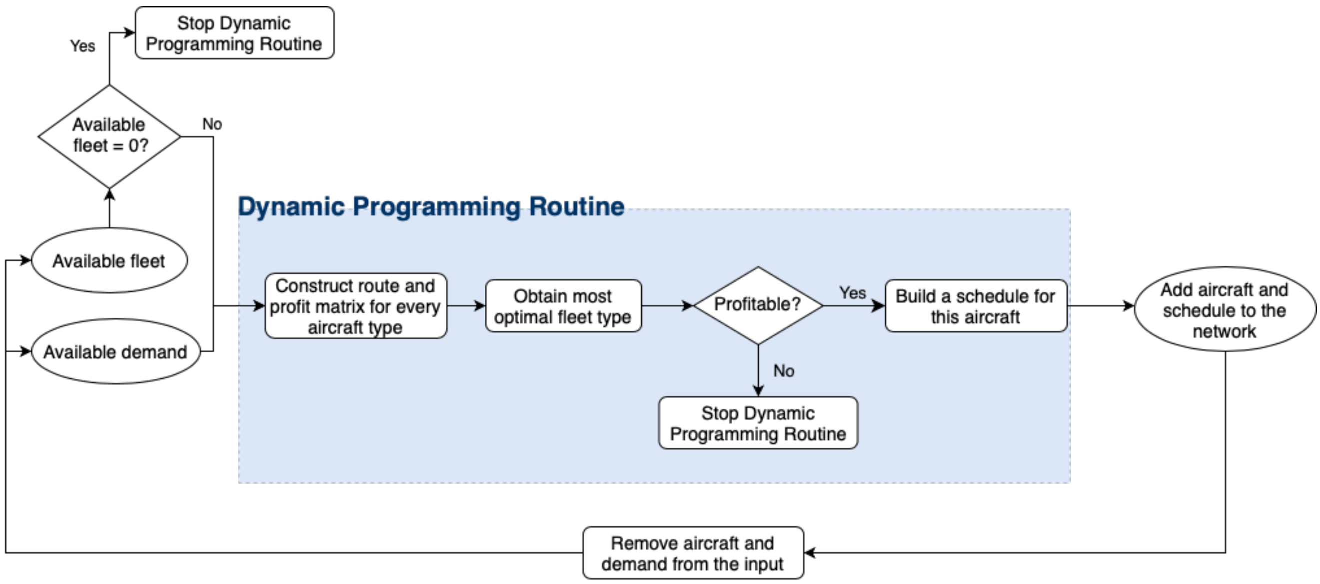

Figure 2: Normal flow of the Optimization Routine.

As can be seen in the figure, the problem starts with the available fleet and demand as input. Given each aircraft and all the available stations in the network, a profit is computed for each of the vehicles to fly to each destination in the upcoming time step. From the most profitable route, a destination for each vehicle at each time step is included in the route matrix. The profit associated with this route is also included in the named profit matrix. After both matrices are completed for every aircraft type, the one that generates the most profit for the airline is chosen. In the case the profit is negative, the dynamic programming routine is set to end. If the most profitable aircraft in the available fleet generates negative profit, it is not necessary to analyze any further. If this profit has a positive value, the aircraft is assigned a route for the entirety of the planning horizon. The schedule associated with this route is added to the network schedule, and the aircraft and served demand are removed from the input. The process ends when there are no more available vehicles in the fleet. The assumption that each aircraft can be studied separately and added to the network sequentially results in a compromise in optimality of the final result.

4.1 Problem Logic

The individual study of each aircraft is based on the construction of a profit and a route matrix. Starting at the final time step, profit is computed for all possible routes departing from each station. The profits are then compared and the destination associated with the maximum value is added to the route matrix as the optimal decision. In addition, the associated profit to that decision is added as the weight for the node. Figure 3 and 4 are a graphic representation of this process.

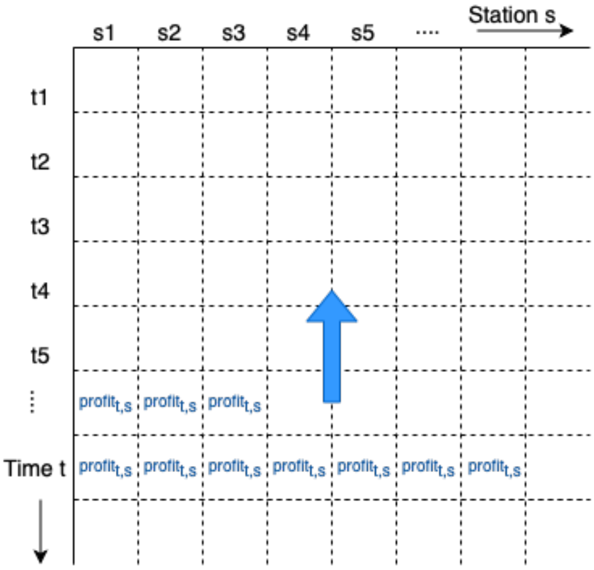

Figure 3: Profit Matrix.

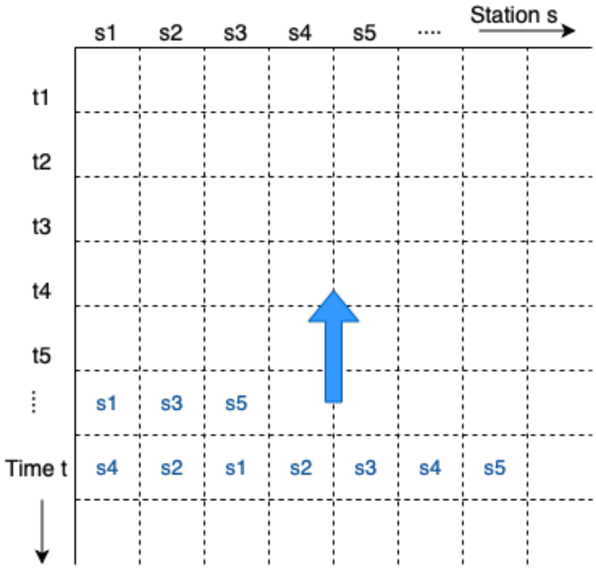

Figure 4: Route Matrix.

The variables included in the process are derived from Powell [2011] as follows:

- State variable (S_1,..., S_n,..., S_N): contains the value of the profit at each node, this information is used at each node to make the decision to fly somewhere else or stay in position. It also shows the evolution of the problem.
- Decision variable(x_1,...,x_n,...x_N): is the optimal decision at each node, it can be to stay in position or fly to another location.
- Contribution function $C_n(S_n, x_n)$: represents the contribution of the present stage to the total profit and it depends on the current state (S_n) and the decision made (x_n). It is influenced by the demand that is available for a specific route inside the attraction band.

From this formulation, Bellman's optimality equation (Equation 1) is derived to obtain the profit weight of every node. Here $V_{n+1}(S_{n+1})$ represents the value of being in state S_{n+1} and γ is the discount factor arising from the fact that it refers to a future stage.

$$V_n(S_n) = \max_{(x_n \in X_t)} (C_n(S_n, a_n) + \gamma \mathbb{E}[V_{n+1}(S_{n+1})|S_n]) \quad (1)$$

When the sub-process is finished, and both profit and route matrices are available for all aircraft, the model will devise optimal routing for the most profitable vehicle by following the decisions outlined in the route matrix (see Figure 5). This process is defined as the forward propagation of the model, where passengers are subsequently assigned to each flight and the demand is updated. After a complete route is assigned to an aircraft, said vehicle is removed from the model, and the routes and profit matrices are recalculated for the remaining ones. The process is repeated until every aircraft is assigned to a route. The general behavior of the problem is to expend backward while creating the matrices and then propagate forward when creating the schedule. It can be said that it is a back and forth process, repeated as many times as the total number of aircraft in the input. One requirement that is fed into the simulation is that every aircraft should start and end the modeled period at the airline hub. This is done by assigning a high value to the matrix entry that corresponds to the last time-step at the station that serves as the hub. Note that, to avoid flights departing within the curfew times of each airport, the model automatically adds as a decision to stay in position when the time step falls inside of the curfew for that specific station.

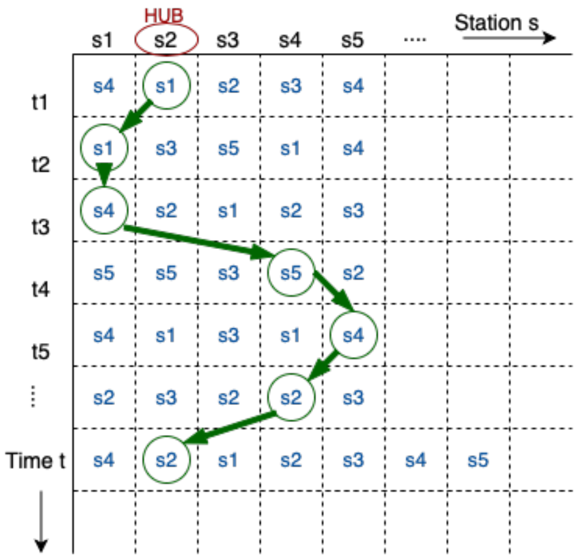

Figure 5: Decision Matrix for the Dynamic Programming Subroutine.

4.2 Demand Update Function

One of the requirements for building a fleet assignment using dynamic programming, is that the demand is updated every time the "most optimal aircraft" is assigned a route and schedule, and therefore removed from the optimization problem. The demand is presented as weighted points that distribute over the studied period, one week. An example for the demand distribution of one route is presented in Figure 6, note that it is spread over multiple time steps to emulate the attraction band of said route. The attraction band is the time period, before and after the considered flight time, within which passengers can be captured.

Figure 6 represents the unconstrained demand for a set route. After any certain flight is added to the schedule, the allocated demand is obtained from the minimum number between the unconstrained demand and the aircraft capacity. Given that the demand is defined as a distribution between multiple time steps, there is the need to define an attraction band. For this research, an attraction band of 24 hours is considered to capture passengers. This large time period is comes from the assumption that long-haul passengers do not have a strong preference to travel on a certain day. This means that a flight at time t could capture passengers from the demand between t-24 hours and t+24 hours. After the total demand allocated to a certain flight is known, the remaining route demand is updated. The served number of passengers is subtracted from the original demand function to create an input for the next optimization problem. Previous research presents demand update functions based on reducing the values evenly for the entire duration of the attraction band. However,

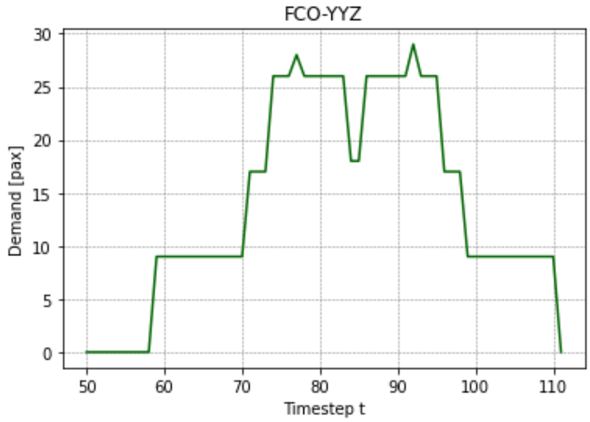

Figure 6: Demand distribution throughout the day.

this study follows the method proposed by Wang [2016], which states that demand should be reduced to 0 at the departure time step and the subtraction should propagate in both directions towards the limits of the attraction band, as shown in Figure 7. This approach ensures that flights are placed at times at which demand is peak, as opposed to any other location within the attraction band.

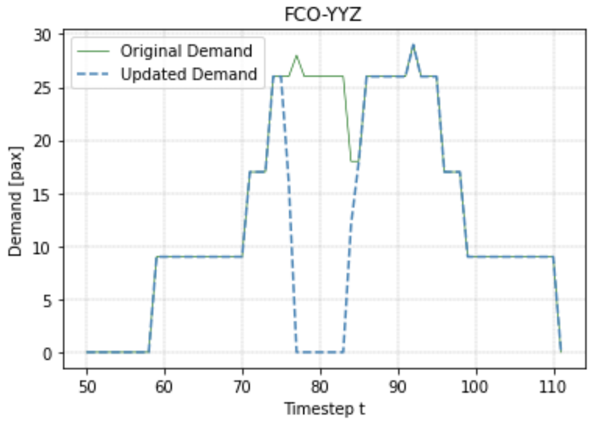

Figure 7: Updated demand after 200 passengers are assigned to a flight at time step 20.

4.3 Cost and Revenue Calculations

Similar to any optimization problem, dynamic programming relies on identifying an objective and working towards maximizing or minimizing its value. When proposing the implementation of operational changes within an airline network, the changes should be proven to benefit the business. Therefore, the objective of this problem is to maximize the profit generated from the designed operations.

Revenue and cost calculations are greatly based on the method proposed by Woudenberg [2019], adapting said research to passenger flights rather than cargo. Revenue is straightforwardly obtained from the price at which passengers purchase their tickets. The ticket fares are included as an input for the model, and they vary based on the route. Operating costs are dependant on the route, number of passengers, block time, and the fuel burnt. Note that the introduction of intermediate stop operations results in different amounts of fuel burnt for the same route, this is why both factors should be considered independently for the calculation. Operating costs arise from 7 categories mainly: airport costs, navigation costs, fuel costs, crew costs, maintenance costs, ownership costs and CO_2 costs. Wang [2016] divides the airport costs between landing and take-off fees and ground-handling fees, both determined as a function of the number of passengers on board. Navigation costs are obtained from the MTOW and the flight distance , and refer to those that appear on-route, as opposed to terminal navigation rates, which are assumed to be included within the landing and take-off fees. Fuel costs are determined by the amount of fuel burnt and the required reserve fuel. Wink [2020] proposes the method in equation Equation 2 to calculate the required flight fuel based on the payload weight and the range. To account for the extra fuel consumption associated with take-off and landing, 100 km are added to the range for the fuel calculations.

$$W_{fuel} = (W_0 + W_p) \left(e^{\frac{RC_D C_T}{VC_L}} - 1 \right) \tag{2}$$

Crew costs are obtained based on the minimum crew requirements from the aircraft specifications and similarly, maintenance costs are derived from the aircraft utilization. Ownership costs are determined on an hourly basis and multiplied by the block time. These costs include investment, depreciation, interest and insurance. Finally, CO_2 charges are included to penalize flights with higher emissions. The price of the ton of carbon dioxide is defined by the European Trading Scheme (ETS). The calculation of CO_2 charges and fuel costs represent the most relevant addition to the cost calculation since it introduces the distinction between ISO and non-ISO flights inside the dynamic programming subroutine.

4.4 Optimization Model Formulation

From the model outline described in the previous section, the problem formulation is derived based on that of Wang [2016]. The sets that describe the network are: S: set of cities, or stations, indexed by i (origin), k (destination) or h (hub); J: sets of fleet types, indexed by j; L: set of possible flights, indexed by ik o; T: set of event times at all stations, indexed by t; N: set of nodes in the time-space network, indexed by jit. The main decision variable is $f_{j,l}$, which equals 1 if aircraft of type j is assigned to flight l, and 0 otherwise. The objective function is then defined as the summation of the profits of all operated flights:

$$\text{Max} \sum_{i,k \in L} \sum_{j \in J} profit_{j,i,k} \times f_{j,i,k} \tag{3}$$

Finally, it is left to discuss the constraints under which this model operates. These constraints are included in the DP formulation when building the aforementioned route and profit matrices. If a constraint is violated, the assignment of that specific route by the considered vehicle is rejected. When the profit resulting from this assignment is the maximum achievable, the model still rejects the option given that it violates one or more of the constraints presented below:

- The number of passengers assigned to one flight ($x_{\{ikj\}}$) shall not be higher than the demand for that route and inside the time attraction band:

$$x_{\{ikj\}} \leq Demand_{\{ik\}} \qquad \forall \{ik\} \in L \tag{4}$$

- The number of passengers assigned to one flight shall not be higher than the available aircraft capacity:

$$x_{\{ikj\}} \leq Capacity_j \qquad \forall \{ik\} \in L \qquad and \qquad \forall \{j\} \in J \tag{5}$$

- An aircraft shall not be assigned to route ij if the flight distance between i and j is higher than the aircraft range:

$$distance_{x_{\{ikj\}}} \leq Range_{\{j\}} \qquad \forall \{ik\} \in L \qquad and \qquad \forall j \in J \tag{6}$$

- An aircraft shall not be assigned to route ij if the runways at either i or j are shorter than the aircraft take-off or landing distance:

$$TakeoffDist_j \leq RunwayLength_i \qquad \forall j \in J \qquad and \qquad \forall i \in N \tag{7}$$

$$LandingDist_j \leq RunwayLength_k \qquad \forall j \in J \qquad and \qquad \forall k \in N \tag{8}$$

5 Climate Effect Modelling

The main goal of this research is to quantify the potential environmental savings of operational improvements. As previously stated, multiple compounds generate radiative forcing (RF) creating what we commonly know as global warming. These compounds are a product of fuel combustion in the engine, and upon interaction with the atmosphere, they result in both warming and cooling effects. Consequently, the impact of these substances is related to the amount of fuel burnt and it is affected by the flight altitude and conditions. The potential emission savings given from the implementation of intermediate stop operations could be simply visualized by comparing the emission quantities for both scenarios. Nevertheless, this approach does not allow for a common study of the effect of different species, and the factual consequences for climate change in the long term. According to Grewe and Dahlmann [2015], the most suitable metric is the Average Temperature Response (ATR), which represents the mean change in the Earth's surface temperature for a given time horizon. For a time horizon of H years, the average temperature response (in Kelvin) is calculated as follows :

$$ATR_H = \frac{1}{H} \int_t^{t+H} dT(t)dt \tag{9}$$

In this equation, t represents the initial measurement time, while H refers to the planning horizon period. Moreover, dT represents the temperature variation arising from the radiative imbalance in the atmosphere. Typically, frames of 20, 50, or 100 years are used. Given that certain compounds have a higher atmospheric residency than others, this study uses 100 years to account for long and short-term effects. The contribution of the different emissions to ATR_{100} is based on the individual contribution to the temperature variation (dT). Grewe and Stenke [2008] present the calculation of the temperature change per year as shown in Equation 10.

$$\Delta T(t) = \int_{t_0}^{t} G_T(t-t') \cdot RF^*(t')dt' \qquad \text{with} \qquad G_T(t) = \frac{2.246}{36.8} e^{-t/36.8} \tag{10}$$

$G_T(t)$ is the impulse response function, which describes the response to a forcing at time t. $RF^*(t')$ represents the normalized radiative forcing that is generated by the emissions. The normalized value is obtained by adding each compound's individual RF divided by the $RF_{2\times CO_2}$. This factor represents the radiative forcing arising from a doubling in carbon dioxide concentration as compared to pre-industrial times. As it can be seen in Equation 11 these values are also multiplied by the efficacy of each species Eff_i. The individual efficacies are given by the ratio of its climate sensitivity and that of CO_2.

$$RF^*(t) = \sum_{i}^{\text{all species}} RF_i^*(t) = \sum_{i}^{\text{all species}} \left[Eff_i \cdot \frac{RF_i(t)}{RF_{2\times CO_2}} \right] \tag{11}$$

This equation should be applied to all contributing emissions except for carbon dioxide, for which its contribution is already normalized. The specific procedures used to calculate the radiative forcing of each species are described in the upcoming sections.

The network plan resulting from the simulation in Figure 2 provides a week-long schedule, consequently, the fuel consumption obtained refers to the flights within that week. The calculations here described for the modeling of climate effects require inputs measured for one year. It is not realistic to assume that one airline operates under the same conditions for 12 months, therefore, seasonality is included. The fuel consumption, as well as the flown distance, are adapted to account for peak and low periods according to airline data. Furthermore, the average temperature response is calculated for the upcoming 100 years, it should be noted that no growth is included in the simulation. This is because relevant results for this research relate to potential improvements to the current situation, and so any changes to the current state are not pertinent.

5.1 Carbon Dioxide

Koch et al. [2009] describes carbon dioxide (CO_2) as a gas with constant dispersion rate and with an atmospheric lifetime between 100-1000 years. These two factors make emission location irrelevant for this compound's contribution to warming effects. The emission of CO_2 into the atmosphere generates positive radiative force, which translates into warming effect. The approach introduced by Proesmans and Vos [2021] is used to estimate the normalized radiative forcing of CO_2. Firstly, the concentration change in the atmosphere is obtained using the convolution integral in equation Equation 12. The impulse response function $G_{\chi_{CO_2}}$ is obtained following the method described in Sausen and Schumann [2000], and so are the α_i and perturbation lifetime τ_i coefficients.

$$\Delta_{\chi_{CO_2}}(t) = \int_{t_0}^{t} G_{\chi_{CO_2}}(t-t') \cdot E_{CO_2}(t')dt' \qquad \text{with} \qquad G_{\chi_{CO_2}}(t) = \sum_{i=1}^{5} \alpha_i \cdot e^{-t/\tau_i} \tag{12}$$

The absolute emissions of carbon dioxide (E_{CO_2}) are obtained by multiplying the fuel flow and the emission index of this compound, 3.16 kg of CO_2 per kg of kerosene. This concentration variation is transformed into normalized radiative force using Equation 13, where the basis concentration of CO_2 ($\chi_{CO_2,0}$) is assumed to equal 380 ppmv.

$$RF^*(t) = \frac{1}{ln2} \cdot ln\left(\frac{\chi_{CO_2,0} + \Delta_{\chi_{CO_2}}(t)}{\chi_{CO_2,0}}\right) \tag{13}$$

5.2 Nitrogen Oxides

Nitrogen oxides (NO_x) are not the direct cause of atmospheric perturbations. Dessens et al. [2014a] state that the contribution of NO_x to global warming arises from its ability to increase ozone (O_3) concentrations and to reduce the amount of methane (CH_4) in the atmosphere. To accurately describe the effects of NO_x it is necessary to divide its effects between the short and the long term. The most significant contribution to climate change arises from the short-term formation of ozone. This gas has an atmospheric residency time between days and weeks. Ozone-generated radiative forcing is dependant on the altitude of the emissions and is calculated as shown in Equation 14 (Proesmans and Vos [2021]).

$$RF_{O_{3s}}(t,h) = s_{O_{3s}}(h) \cdot \left(\frac{RF_{ref}}{E_{ref}}\right)_{O_{3s}} \cdot E_{NO_x}(t) \tag{14}$$

Here, the term s(h) is a forcing factor added to account for the influence of the altitude of the emissions. The influence of each substance is determined by the altitude at which they mix with the atmosphere. In this study, the altitude is assumed constant at 12,000 km. RF_{ref}/E_{ref} is a constant that represents the relationship between emissions and radiative forcing generated. Contrary to CO_2, the emission index of NO_x is not constant but depends on the engine's technology and operating conditions. Since these factors are unknown at this stage of the research, a constant emission index is assumed and obtained from the research presented by Wasiuk et al. [2016]. In addition to the aforementioned, NO_x also contributes to long-term depletion of both ozone and methane. The radiative forcing arising from these long-term emissions is obtained using Equation 15 for both CH_4 and O_3 (Proesmans and Vos [2021]).

$$RF_i(t,h) = s_i(h) \int_{t_0}^{t} G_i(t-t') \cdot E_{NO_x}(t')dt' \qquad \text{with} \qquad G_i(t) = A_i \cdot e^{-t/\tau_i} \tag{15}$$

Although the depletion process results in a cooling effect, the overall impact of NO_x can be summarized as warming due to the higher contribution of short-lived ozone. Two major assumptions are included in these calculations. First, the combined interaction of ozone creation and depletion is not considered, this means that long and short-term effects are not analyzed jointly. Moreover, the location of the emissions is assumed irrelevant.

5.3 Water, Soot and Sulfates

The contribution of water, soot and sulfates can be modeled in a similar matter to short-lived ozone. Equation 16 is used to obtain the radiative forcing for each of the three compounds (Dallara et al. [2011]).

$$RF_i(t) = \left(\frac{RF_{ref}}{E_{ref}}\right)_i \cdot E_i(t) \tag{16}$$

Note that in this case, the influence of altitude is not necessary for the calculations (Proesmans and Vos [2021]). In addition to their contribution to climate change, soot and sulfates play a major role in the deterioration of local air quality.

5.4 Contrails

Condensation trails are phenomena included within the short-term effect of aviation-induced cloudiness. Contrails form when the mixing of exhaust gases with ambient air reaches the saturation levels of liquid water (Koch et al. [2009]). The radiative forcing generated by these line-shaped clouds is obtained from Equation 17, similar to short-lived ozone.

$$RF_{contrails}(t) = s_{contrails}(t) \cdot \left(\frac{RF_{ref}}{L_{ref}}\right)_{contrails} \cdot L(t) \tag{17}$$

Here, Dallara et al. [2011] define L as the stage length flown, typically per year. For this research, the impact of altitude is partially considered within the forcing factor s. However, this factor relates to altitude-dependant impact, while it is left for further stages to analyze the influence of altitude and location for the formation of contrails, as presented by Fichter et al. [2005].

6 Case Study: Alitalia Long-haul Operations

In order to test the methodology described in the previous section, a synthetic case study was generated. Due to the European competency of the ClimOp project, a European airline is chosen as the object of study. To test Intermediate Stop Operations, long-haul flights should be modeled. Alitalia services long-haul routes to North and South America and Asia, making it a prime candidate for the subject. The routes selected for the analysis can be observed in Table 1. Note that the return route is also considered, but not necessarily assumed to have equal demand. The airport of Rome, Fiumicino serves as the hub for this airline, this means that when the schedule is designed, the forward propagation starts at this location.

Table 1: Long-haul routes from Alitalia considered in the case study.

Origin City	Origin IATA Code	Destination City	Destination Country	Detination IATA code
Milan	MXP	Abu Dhabi	UAE	AUH
Venice	VCE	Abu Dhabi	UAE	AUH
Rome	FCO	Buenos Aires	Argentina	EZE
Rome	FCO	Chicago	USA	ORD
Rome	FCO	Los Angeles	USA	LAX
Milan	MXP	New York	USA	JFK
Milan	MXP	Shanghai	China	PVG
Milan	MXP	Tokyo	Japan	NRT
Rome	FCO	New York	USA	JFK
Rome	FCO	Rio de Janeiro	Brazil	GIG
Rome	FCO	Miami	USA	MIA
Rome	FCO	Sao Paulo	Brazil	GRU
Rome	FCO	Seoul	South Korea	ICN
Rome	FCO	Tokyo	Japan	NRT
Rome	FCO	Toronto	Canada	YYZ

From Alitalia, the operative long-haul fleet is selected: 6 Airbus 330-300 and 6 Boeing 777-200ER. In addition, two A320-200 from the short-haul fleet are added to potentially operate the shorter flight legs arising from the implementation of ISO. The technical specifications for these aircraft are obtained from manufacturer data and from regulating agencies. The complete set of data used can be found in Appendix A.

6.1 Demand Construction

Since real demand data was not available for this research, a synthetic set is generated to use as input. The set of Alitalia flights is obtained for the year 2015 from SkyTeam data. Since the goal is to produce a weekly schedule, data should be acquired for a 7-day period. Assuming that airlines experience their peak period over the summer, data is collected between the 12th and 19th of July to ensure most offered flights are captured. The potential number of passengers that are transported in these flights is given by the capacity of the aircraft that operates them. Given the time at which these flights occur and the number of passengers that are transported, a distribution of the demand is generated as seen in Figure 8.

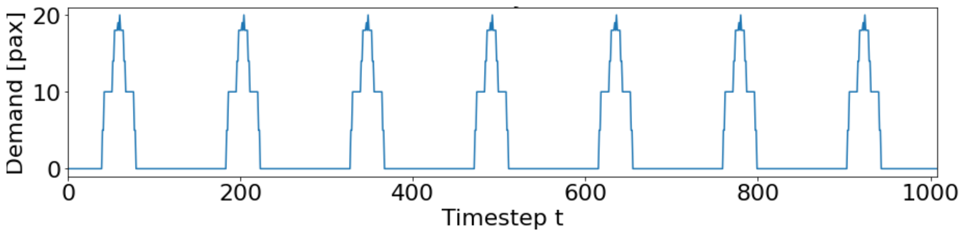

Figure 8: Weekly demand for the route Rome - New York.

As it can be observed in the figure, the demand is not a single peak observed in the time of the flight, but rather, it is represented as a distribution over a certain attraction band. As it was previously explained in subsection 4.2, passengers are assumed to be captured three hours before and three hours after their preferred times. For instance, when modeling the route in the figure, flights depart every day of the week at 9:40 am. This hour translated into model time results in step 58 for the flight on Monday, step 202 for the flight on Tuesday, and so on. The image shows that the peak of the passengers are assigned to the demand at those points, however, a smaller distribution is located in the time steps that belong to the attraction band.

In addition, flights operated by other airlines but also serving the aforementioned routes are considered and included in the demand model. This extra demand is added to that of Alitalia at the time at which the other airline has that route schedule. However, only 10% of the passenger capacity for the extra flights is considered, since it cannot be accurately predicted if those passengers could be captured by Alitalia. Figure 9 shows a close-up look of the demand for one day for the route Rome - New York. It can be seen that there is an extra peak at time step 60. This is because American Airlines operates a flight for the aforementioned route at 10 am every day, and thus extra passengers can be captured around that time.

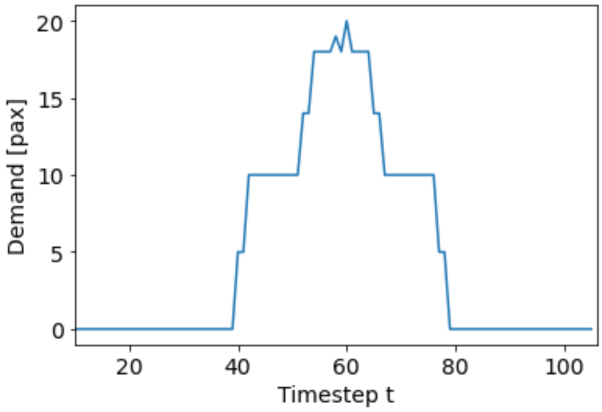

Figure 9: Daily view of the demand for the route Rome - New York.

6.2 ISO Locations

For each of the routes in the case study, there is a proposed stop-over location. This stop is chosen by looking at flight routes and locating international airports that are closest to the route mid-point. However, some of the routes' mid-points happen above underpopulated areas or above the ocean, therefore the stop location is not optimal. The highest increase in route length with the introduction of a stop is 125 km, however, the average deviation stays low at 31.4 km. The full set of routes with stops can be seen in Figure 10 and 11.

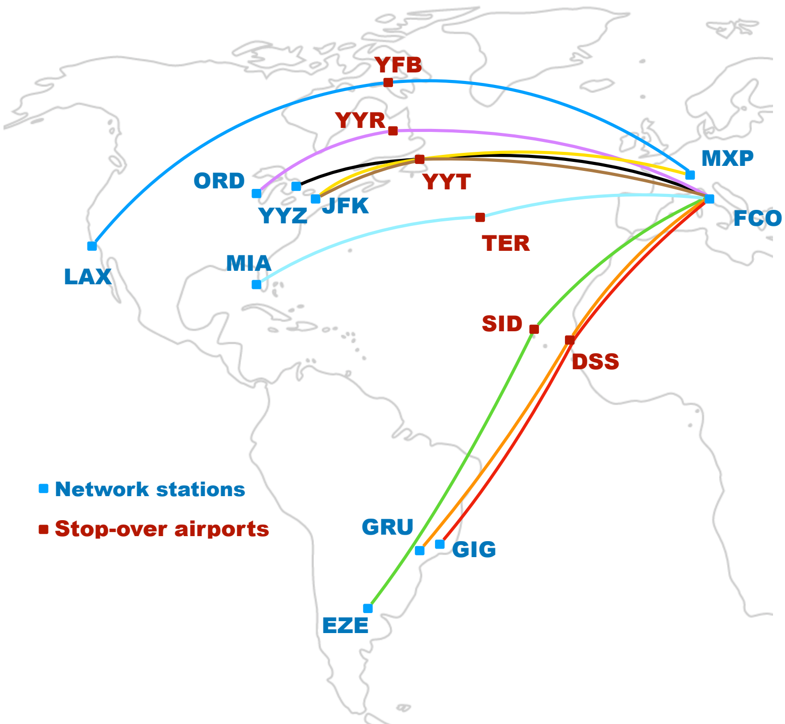

Figure 10: Westbound routes and their corresponding stop locations.

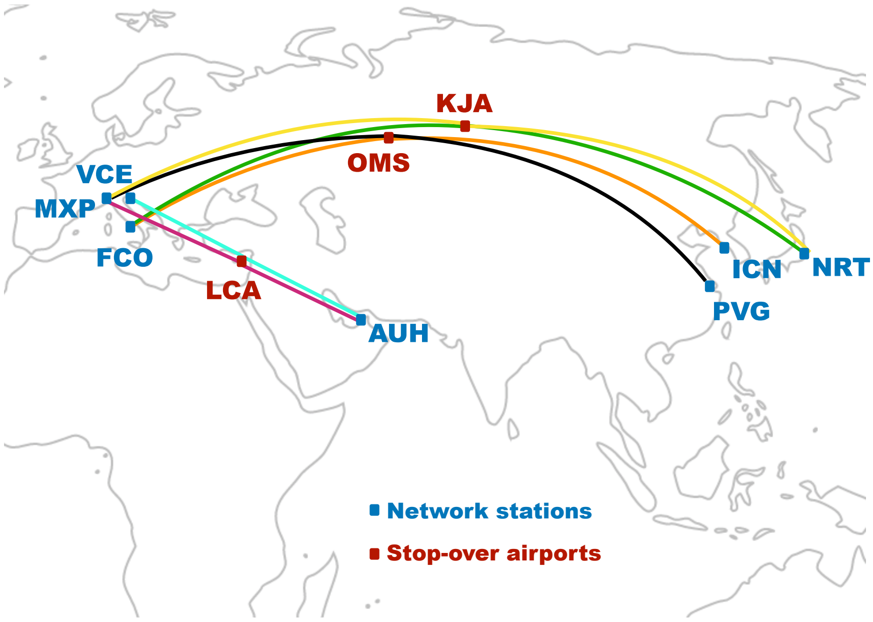

Figure 11: Eastbound routes and their corresponding stop locations.

6.3 Data Set Assumptions

Due to the lack of official data, some of the parameters included in the input data set have been estimated. Therefore, their value is considered an assumption that can be extracted from the model if more precise data is available. These assumptions are:

1. Airport curfew is equal and applicable at every location. No flights are allowed to depart between 11pm and 5am. This value is obtained from the original Alitalia schedule, for which the majority of departure times fall within these limits.
2. Airport costs, such as LTO fees, ground handling charges and parking fees are assumed to be equal at every location. The value for the parking fees is set at $0.14 per hour per ton of maximum take-off weight, as set by the competent authorities (*ADR - Aeroporti di Roma*). Other values are obtained from the research of Woudenberg [2019].
3. En-route navigation charges are assumed to be constant throughout the various airspaces it travels. The navigation charges are set at $180 per service unit and obtained from Eurocontrol.

7 Results

The potential implementation of ISO in modern aviation is determined by its ability to perform better than its alternative. This performance is defined by operational, economical and environmental indicators. Note that the results presented in this section are greatly dependant on assumptions. These assumptions are introduced by the technique used to create the fleet assignment model, but also by the uncertainty surrounding the creation of synthetic data. Therefore, it is crucial to analyze results in comparison to the case in which ISO is not applied. This contrast gives an indication of the potential network improvements and setbacks, caused by the implementation of ISO. The main assumptions for this study are listed below:

1. The synthetic demand is generated under the assumption that all the flights serving one route are operated by the same aircraft.
2. The altitude of flights is assumed to be constant. No varying flight profile.
3. ATR calculations provide temperature rise in a period of 100 years. During these years no growth is applied to the data. This means results are a sole evaluation of the consequences of the current situation.
4. The weekly schedule is repeated throughout the year. However, there is a seasonality factor considered in the climate effects modeling. Based on airline data, it is assumed that during low season (three months), the traffic is reduced by 20%.
5. For fuel consumption/range calculations, it is assumed that the aircraft flies fully loaded.
6. For the intermediate stop operations, flight time and fuel consumption are calculated separately for both flight legs, and then added together for the total flight value.
7. Taxi and turnaround time are assumed to be solely aircraft dependent. No distinction between different airports for the establishment of these values.
8. Maintenance costs are included within the profit calculation, however, no maintenance breaks are included in the routing and scheduling.
9. Reserve fuel is included in the cost calculation of every flight.
10. Pilot and crew costs are not influenced by aircraft type.
11. The assessment of operational improvements is performed assuming no changes to the current fleet.
12. No extra airport charges are added from the introduction of intermediate stops. This means airport fees are only paid for the departure and final arrival airport.

7.1 Standard Case

The scenario under which the results for the standard case are produced aim to replicate Alitalia's current operations. This means that ISO is not implemented, and therefore it can be used to compare the environmental savings introduced by this operational improvement. Based on the number of passengers to be transported per route and the aircraft available to be assigned, a schedule is created. The model is given the condition that every aircraft must start and the simulation at the hub. Under these conditions, the model produces a total of 108 flights, operated by the wide-body fleet. The six A330 and B777 are given a route assignment in the model, however, the profit added to the network by the A320 is negative, which results in them being discarded from the schedule. These flights transport a total of 37,718 passengers, which leads to a profit generated per passenger of $99. This number should not be considered in its absolute value since many costs were not included in the analysis. It should be used as a basis to compare the application of the climate mitigation strategy. Furthermore, the total fuel burnt equals 9,612 tonnes, 255 kg of fuel per passenger transported. This fuel consumption leads to 0.8 tonnes of CO_2 emitted per passenger transported, and an associated ATR_{100} value is 0.0104 mK. This means that in the next 100 years, these flights will provoke a 0.0104 mK temperature increase of the Earth's surface.

From the schedule obtained for the situation described above, it is observable that the flights differ significantly with respect to Alitalia's orginal schedule. In order to create a situation that resembles reality, a more accurate standard scenario is created. For this scenario, aircraft may choose between Rome or Milan as their start and end location, based on what situation generates more profit. For the model formulation, this means that both stations can be considered as hubs. During the dynamic optimization process, the start and end location for the planning will vary between both stations based on profit maximization. This new condition causes the model to plan 112 flights, and same as the previous case, all operated by the wide-body fleet. The number of passengers transported is 38,525, leading to a profit per passenger of $109, and a total of 250 kg of fuel burnt per passenger transported. The fuel consumption is translated into 0.79 tonnes of CO_2 emitted per passenger transported, and the total value for ATR_{100} equals 0.0106 mK. A summary of the results for both standard scenarios can be seen in Table 2. Future results are constructed from the assumption that both FCO and MXP serve as hubs for the airline.

Table 2: Standard Case Results for the 1 hub versus 2 hubs situation.

Hubs	Number of flights	Number of passengers	Fuel / pax [tonnes]	Profit /pax [USD]	ATR_{100} [mK]
FCO	108	37,718	0.255	99	0.0104
FCO & MXP	112	38,525	0.250	109	0.0106

7.2 ISO Implementation

Testing the implementation of ISO consists of giving the model the choice of splitting a flight into two legs when this option results more profitable. The increase in profitability is caused by a reduction in the fuel required for the route. Initially, the model is instructed to implement ISO on routes above 7,000 km if stopping at the airports proposed in subsection 6.2 results more profitable. However, the resulting schedule, and therefore performance indicators, remains unchanged from the standard scenario. This means that for the network, the fuel savings from the stop-over are outweighed by the extra fuel from the longer flight due to the deviation. Note that the stop-over also introduces extra airport charges, which also present a disadvantage for the strategy.

To provide insight on the implications of implementing ISO, the strategy is tested under the assumption that stop-overs could be performed directly in the middle of the route. This eliminates flight path deviation and the corresponding extra flight distance from the problem. The resultant schedule includes 112 flights, of which 40 are operated with a stop-over. The routes included in this schedule can be observed in Figure 12 and 13. As can be seen in the figures, some input routes are not operated. The total of the A330s and the B777s are assigned to a weekly schedule, however, the A320s remain grounded. One conclusion to draw from these two facts is that operating those routes with the A320s is less profitable than not operating them.

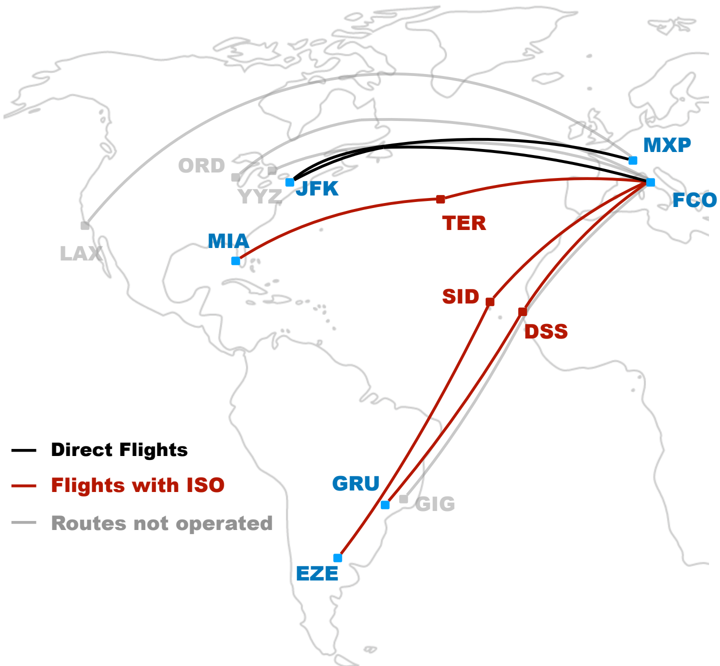

Figure 12: Westbound flights after implementing ISO.

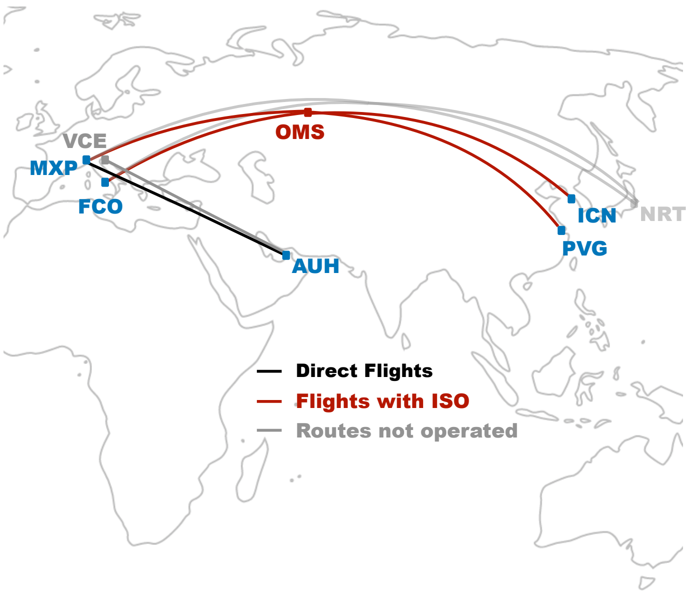

Figure 13: Eastbound flights after implementing ISO.

The number of passengers transported under these conditions equals 38,525, which amounts to 238 kg of fuel burnt per passenger. Profit per passenger equals \$112 and 0.75 tonnes of fuel are burnt per passenger. The climate impact associated with this network is an ATR_{100} value of 0.0105 mK. For a comparative analysis, relative values to the standard case (no ISO applied) can be observed in Table 3. ISO is tested under the condition that both FCO and MXP can be utilized as hubs and therefore, results should be compared to the dual hub standard case.

Table 3: Results of implementing ISO relative to the standard case

Number of passengers	Fuel /pax [tonnes]	Profit /pax [USD]	ATR_{100} [mK]
+0%	-4.9 %	+2 %	-0.1%

As the table shows, by implementing stop operations in flights over 7000 km, a reduction in the climate impact is achieved without compromising the number of transported passengers. Fuel savings of around 5% can be achieved without a profit loss. The main negative aspect of these results is that for each of the flights that fly with a stop-over, there is an extra flight time of 1 hour, associated with the additional landing, refueling and take-off operations.

7.3 Sensitivity Analysis: Minimum ISO Distance Variation

Previous studies on the viability of ISO suggest that its implementation is only advantageous in flights between 7,000 and 10,000 km long. In order to study the effect on the threshold distance variation, a sensitivity analysis is performed. For this analysis, the minimum distance required to consider ISO is increased by 1,000 km for each scenario. The results show that the number of total schedule flights and passengers transported remains equal for different minimum distances. However, the number of flights that are operated with a stopover is reduced proportionally with the increase in distance. This outcome is reasonable since the number of flights in which ISO is applicable decreases significantly. The reduction in the ISO-operated flights leads to an increase in fuel consumption and a decrease in the profit generated. The results of the sensitivity analysis can be observed in Table 4.

Table 4: Sensitivity Analysis for a variation in minimum distance to implement ISO.

Minimum distance [km]	Number of ISO flights	Fuel /pax [tonnes]	Profit /pax [USD]
7,000	40	0.238	111.63
8,000	40	0.238	111.63
9,000	24	0.242	111.37
10,000	12	0.245	110.83
Relative change with the increase in minimum distance from 7,000 to 10,000 km			
+ 43 %	- 70 %	+ 3 %	-1 %

Since the total number of flights remains unaltered, increasing the minimum distance results in an increase in the climate impact of the network. Figure 14 shows the effect of these scenarios in the ATR_{100} values. Note that this analysis does not include considerations about flight profiles. When implementing ISO, the flight altitude of the different legs varies with respect to the direct flights. The change in altitude is translated into a change in fuel consumption and emission interaction. Based on the assumptions from this study, it can be concluded that increasing the minimum distance is not advantageous for the network. However, a more detailed analysis including flight profile considerations could lead to the conclusion that longer distances are beneficial for the network.

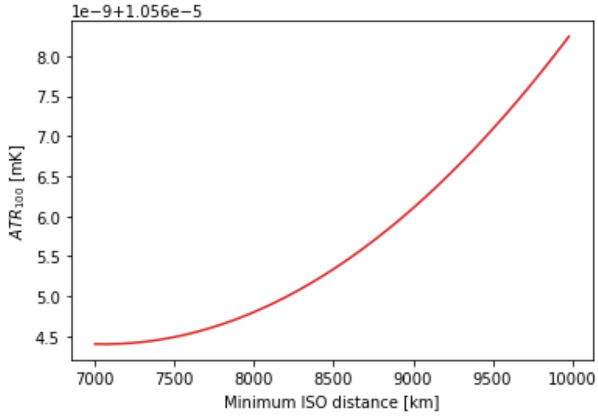

Figure 14: Change in climate impact for a variation in minimum distance to implement ISO.

7.4 Convergence to Original Alitalia Schedule

As a validation for the model results, it is studied whether the schedule that results from the standard case converges to Alitalia's original schedule. The assumptions included in this model, in addition to the synthetic character of the data, make a complete comparison between both schedules unrealistic. The number total number of flights operated in the original schedule equals 196, while the number of flights operated in the standard case of this research stays low at 112. However, from the routes that are operated in both situations, it is observed that the flight times deviate in low quantities. Table 5, shows a comparison in the departure time and the aircraft that operates every route for the original and the model schedule for Monday flights. Time deviations range from 0 to 3 hours, with the average being 1 hour and 40 minutes, meaning that departure times stay significantly close.

Table 5: Comparison of flights for Alitalia´s original schedule and the standard case.

Origin	Destination	Original Deparure Time	Model Departure Time	Original Aircraft	Model Aircraft
FCO	JFK	09:40:00	9:40:00	A330	A330
MXP	JFK	13:00:00	10:40:00	A330	A330
FCO	MIA	10:40:00	13:40:00	A330	B777
JFK	FCO	18:05:00	15:40:00	A330	A330
MIA	FCO	20:35:00	18:40:00	A330	B777
MXP	AUH	22:10:00	22:50:00	B777	A330
FCO	EZE	21:45:00	22:50:00	B777	B777
FCO	GRU	22:05:00	22:50:00	B777	B777
JFK	MXP	20:30:00	22:50:00	A330	A330

The table includes the aircraft assignment for each route, nevertheless, there is no clear pattern to study in the assignment of the two different aircraft, the A330 and the B777. Given the similarities between the capacity and cost characteristics of both aircraft, there is no clear conclusion to be drawn for the aircraft assignment. These flights correspond to the first 24 hours, therefore it is natural most of them have FCO or MXP as their departure airport since all aircraft should start the week at one of the hubs. One main difference, between the model and the original schedule is that higher flight frequency is present for those routes which have flights operated by other airlines. For instance the route MXP - JFK is flown with more frequency than the original schedule since American Airlines and Emirates also operate flights between these two airports.

7.5 Fleet Variation

When comparing the model generated schedule and the original schedule for the airline there is one notorious difference: certain routes are not operated in the modeled schedule. One reason for this could be that the fleet is insufficient or not appropriate. To study this possibility, two scenarios are tested with different fleet distributions. Scenario A studies the variation of results if half of the long haul fleet was replaced by smaller aircraft. While Scenario B studies the possibility of introducing two extra long haul aircraft and reducing to one the short-haul fleet. Despite no A320 being previously assigned a route, the input contains one of these vehicles in case the new fleet generates a variation in the assignment. A summary of the fleet for these scenarios can be observed in Table 6.

Table 6: Different scenarios with different fleet numbers.

	A330	B777	A320
Original fleet	6	6	2
Scenario A	3	3	8
Scenario B	7	7	1

For Scenario A, extra flights were generated, resulting in a total of 126. With a minimum ISO distance of 7,000 km, 42 flights are scheduled with a stopover. The results show, as was expected, that the left A320 is not assigned to any routes. From the long-haul fleet, seven B777 are scheduled, however, only six of the A330 are added. This concludes that the addition of extra aircraft to the long-haul fleet does not result in every route being operated. The fact that certain routes are left out of the assignment is a product of the compromise in optimality from dynamic programming. Certain routes are not added because the flight combination does not result profitable for the airline after the other aircraft have been scheduled.

Regarding Scenario B, results show that the use of a smaller aircraft fleet is not viable for the input routes. Although ISO creates shorter flight legs, using a narrow-body aircraft remains less profitable. For this scenario, a significant decrease in the number of flights is experienced. There is a total number of scheduled flights of 77, being only 8 those operated as ISO. These flights are operated by the 6 remaining long-haul aircraft and one of the proposed eight A320. This shows that the extra capacity provided by the larger aircraft and the different fuel efficiencies, present a clear advantage when creating a fleet assignment. For networks that include routes such as the ones studied in this research, it is not beneficial to substitute aircraft in the fleet with smaller versions.

8 Conclusion

The implementation of ISO in current airline networks provides the benefit of reducing the fuel that is initially loaded onto the aircraft. The fuel cut results in a reduction in the pollutant compounds that are emitted to the atmosphere as a product of combustion. The fleet assignment and network schedule are generated as a framework to test this operational improvement. Dynamic Programming relies on dividing an optimization problem into smaller subroutines that can be analyzed separately. To create a fleet assignment and a network schedule, the problem is once divided into the different aircraft in the fleet, and then into the time steps in the problem. Once a sequential link of decisions is created, the model can then produce results while maximizing profitability. The sequential addition of aircraft to the schedule results in a compromise in optimality. This is a major drawback of dynamic programming, decisions cannot be altered once new information is known. The climate impact assessment portion of the model uses flight distances and fuel burnt as input to calculate potential temperature changes on the Earth's surface. Therefore generating a schedule was not necessary. However, for future research it is beneficial to create a time-based analysis, since weather plays a major role in a more detailed climate impact assessment. Moreover, if the exact combustion conditions are known, a more detailed analysis of the contrail formation could be performed by following the Schmidt-Appleman criterion.

There are five main conclusions to draw from this research. Firstly, the stop locations proposed for the implementation of ISO introduce a large deviation from the original route. This results in a total fuel required for the route detour that is higher than the savings incurred by the implementation of the strategy. This constitutes an impediment for any airline network that serves routes where there are no airports at the midpoint. Particularly, this poses a significant challenge for overseas flights, where most of the route is not flown over land. Secondly, if stopping at an optimal location was possible for every route, there are potential fuel savings introduced by ISO. Under the assumption that there is an airport at the exact mid-point of every route, the fuel consumption per passenger transported is reduced by nearly 5%. The fuel saving translates in a decrease of 0.1% in ATR_{100}, which means that the increase in temperature of the Earth's surface is reduced by 0.0005 K in the next one hundred years. This number might seem minimal, nevertheless, note that this is the impact created by 112 weekly flights of one single airline. If this amount is extrapolated to the total schedule of the airline, and to the total number of airlines in the world, the climate impact savings potential becomes of great significance. The third conclusion relates to the fleet size and type. Contrary to what was expected, the reduction in flight length leg does not result in a preference to use short-haul aircraft. Due to their reduction in seating capacity, the model chooses to continuously operate flights using the long-haul fleet.

The fourth conclusion is associated with the implementation of operational improvements readiness level. Fuel savings result in a decrease in the climate impact of aviation. Reducing emissions is one of the main goals for research in the aviation field. However there are certain factors to be considered when studying the implementation of improvements. As with any airport operation, the introduction of stop-overs can result in flight delays and other disruptions for passengers. The social consequences of this strategy should be considered at the same level as environmental and economical indicators. It is concluded that the current infrastructure would have to be modified to accommodate ISO flights. The location of the stop-over airport plays a big role in the determination of ISO feasibility. In addition, the appropriate refueling stations should be set without the need for the aircraft to be assigned a regular slot. This research shows that implementing ISO in a current airline network is strongly defined by the operated routes and the available fleet. While in optimal conditions environmental savings can be achieved, it is unclear if this operational improvement can be effectively implemented without any modifications to the network.

Finally, from the results in subsection 7.4, it is visible that dynamic programming is a valid technique for the generation of a network schedule. Consequently, it can be stated that it is a viable approach for the testing of operational improvements such as ISO. Given the many assumptions considered for the model creation, the methodology proposed in this paper is not fully developed, nevertheless it can be used as a baseline for future and more detailed research.

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A Aircraft Data

Aircraft type (unique)	Fleet size	Body type [narrow or wide]	Purchase price [M US $]	Spare parts investment [% of purchase price / 100]	Depreciation period [years]	Residual value [M US $]	Yearly interest rate [% / 100]	Yearly insurance rate [% of purchase price / 100]	Maximum load factor [% / 100]	Average load factor [% / 100]	Minimum daily utilisation [block hours]
Type	**Available**	**Body_type**	**Purchase_p**	**Spare_parts**	**Depreciation_**	**Residual_va**	**Interest_rate**	**Insurance_rate**	**Maximum_l**	**Average_loa**	**Minimum_utilisatio**
A320	2	narrow	101.000	0.15	18	10.1	0.09	0.005	0.9	0.9	0
A330	6	wide	241.700	0.15	18	24.17	0.09	0.005	0.9	0.9	0
B777	6	wide	261.500	0.15	18	26.15	0.09	0.005	0.9	0.9	0

Average daily utilisation [block hours]	Takeoff distance at MTOW at IAS conditions [m]	Landing distance at MLW at IAS conditions [m]	Turn around time [hr]	Taxi time & approximation per flight [hr]	Minimum duration of a maintenance activity [hr]	Time required for weekly maintance actions [hr]	Average speed [km/hr]	Minimum Passenger capacity	Maximum Passenger capacity
Average_utilisation	**Takeoff_distance**	**Landing_distance**	**TAT**	**Taxi_time**	**Minimum_mainten**	**Required_maintenar**	**Speed**	**Pax_min**	**Pax_max**
14	1900	1400	1	0.1	3	7	955	140	180
14	2200	1650	2	0.1	3	8	821	250	440
14	2900	2500	2	0.1	3	8	1037	300	440

Maximum takeoff weight [tonnes]	Operational empty weight [tonnes]	Range at maximum payload [km]	Fuel reserve [% of MTOW]	Number of engines	Fuel price per kg [US $/kg]	Maintenance cost per block hour [US $/hr]	Average total flight crew salary [US $/year]	Number of crews per aircraft	Aircraft parameter C
MTOW	**OEW**	**Max_payload**	**Fuel_reserve**	**Engines**	**Fuel_price**	**Maintenance_c**	**Crew_salary**	**Crews**	**C_fuel**
78	42.6	6100	0.05	2	0.45	342	85000	5	25972
233	109	13450	0.05	2	0.45	550	85000	8	28931
297.55	138.1	14310	0.05	2	0.45	800	85000	8	25594

Figure 15: Aircraft Data

II

Literature Study
Previously graded under AE4020

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Literature Study
Assessment of operational improvements to reduce climate impact

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Abstract

The development of a globally linked society creates the need for extensive transportation networks around the globe. Commercial aviation demand grows in line with this need. However, this growth presents a problem regarding the environmental impact of this sector. In the past years, air transport is the source of a fifth of the greenhouse emissions in Europe, creating a threat for climate change and local air quality. The international character of aviation makes national measures unsuccessful. The ClimOp project represents the efforts of the European Commission to research operational improvements to reduce climate impact. This literature study aims to research modelling frameworks to assess strategies such as the introduction of intermediate stop operations, the switch between Hub-and-Spoke and Point-to-Point networks, the trade between the size of aircraft and flight frequency, and the reduction of flight altitude and speed. In order to establish the emissions saving potential and the general impact on economics, operations and safety performance indicators, an airline model is to be set-up by using dynamic programming. This allows for a multi-stage decision approach with the network schedule and fleet assignment as its outputs.

Keywords Airline Operations · Sustainability · Emissions · ClimOp

Executive Summary

The growth of the commercial aviation market raises the concern on its environmental effects. Measures are taken in multiple fields to ensure a more sustainable air transport. The consequences of aviation on the Earth's atmosphere arise from the substances that appear as a product of fuel combustion. These substances create a radiative imbalance that drives the Earth to new equilibrium temperatures, this process is known as "Global Warming". In addition, particulate matter from the engine exhaust has a negative effect on local air quality. Aircraft technology is investigated in order to improve efficiency and limit the amount of fuel burnt. Moreover, existing alternative energy sources such as biofuels or electric aviation are not considered a viable replacement in the near future. IATA defines the road to a more sustainable aviation as a 4-pillar strategy: the improvement of aircraft and fuel technologies, the implementation of more efficient operations, the improvement of currently-used infrastructure and the creation of a single Global Market-Based Measure to fill the remaining emission gap. ClimOp represents the efforts of the European Commission to contribute to the second pillar. The goal of this project is to propose and assess operational improvements, studying their environmental impact in the mid-to-long term (i.e. decadal).

Transportation means are the source of a fifth of the greenhouse gas emissions in Europe. Relevant products of combustion include carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), water vapour (H_2O), and in smaller amounts: hydrocarbons (HC), carbon monoxide (CO) and soot. These substances generate atmospheric perturbations which result in radiative forcing (RF). The effect of certain compounds is maximized at certain altitudes and locations, for instance, water vapour generate positive RF (warming potential) in the stratosphere, due to naturally low humidity levels. Besides these substances, the mixing of exhaust gases with really cold ambient air results in the formation of contrails. These line-shaped clouds can transport into cirrus clouds, changing water budget and optical characteristics of other clouds. The main metrics used to define climate change potential present a major disadvantage, as the used variables become more relevant and clear, the uncertainty surrounding their measurement increases.

In order to evaluate the effectiveness of the model, certain operational improvements are proposed for testing. Intermediate Stop Operations (ISO) focuses on reducing the amount of fuel carried on-board the aircraft, by splitting routes into multiple legs. This means that for long-range flights, a stop is performed to re-fuel and to perform crew-changes. The potential fuel savings for the current fleet is of 4.8%, however, if aircraft with optimized design range are introduced, the fuel savings potential is 11.3%. The second operational improvement relates to the airline business models, these can be divided in Hub-and-Spoke and Point-to-Points networks. The former is formed by a central node, the hub, which is connected to the other destinations. For the latter, direct connections exist between all the nodes. The Point-to-Point model results in lower airport dependency and a decrease in the pollution created per passenger. Furthermore, there is a potential fuel saving in reducing the flight frequency between two destinations, and increasing the size of the aircraft assigned to the route. When analyzing the full flight profile, it is concluded that larger aircraft have a lower contribution to climate change. Medium category aircraft have the smallest per-seat environmental costs. Lastly, the final operational improvement is the reduction of flight altitude to limit the impact of certain substances. In order to avoid a drag increase, the flight speed should also be reduced accordingly.

The previously mentioned operational improvements are modelled by simulating the airline network. The optimization problem can be built using a linear or a dynamic programming formulation. Dynamic programming is based on a multi-stage decision process, for which the original problem is decomposed into multiple subroutines. This approach reduces complexity and computation time. The main elements of the dynamic programming formulation are the state and decision variables. It is built based on Bellman's optimality equation which establishes the value of being in state S as the combination of the decision made at that state and the value of the upcoming state. Using dynamic programming allows generating a fleet assignment and a network schedule within the same optimization model. This is done by defining a time-space network, in which both locations and departures and arrival times are considered for the flight leg assignments. This model requires inputs regarding network capacity, fleet and demand. Initially, airlines have data about the number of passengers that demand a specific route, however, this number needs to be adjusted to meet the capacity of the assigned aircraft. Furthermore, local and transfer passengers should be assigned to the flights following a specific ruling. This is known as the "Passenger Mix Problem" and it ensures connectivity between flights by establishing relationships between the fares that are applied to each ticket type. The dynamic programming approach to airline planning is divided into four major stages: generation of feasible routes, sequential assignment of aircraft routing, passenger assignment and network evaluation, and the sequential reassignment of routings to achieve improved performance.

The assessment model is completed by adding a series of Key Performance Indicators (KPIs). These relevant parameters serve as a metric to establish the value of each operational improvement. Since the final goal of this project is climate effect mitigation, factors such as fuel burnt, Average Temperature Response (ATR) and the local air quality fluctuation index constitute the environmental KPIs. The financial outcome of each strategy is established by calculating economic KPIs, such as the yield, revenue per available seat kilometre and the operating profit. Finally, it is necessary to consider factors such as extra travel time, aircraft productivity and safety, in order to provide a good analysis of the consequences per operational improvement. Impact assessment has been performed in previous studies, such as the Climate Compatible Air Transport System (CATS) project, which provides the climate effect reduction potential for current aircraft and the associated cash operating costs. This research concludes that an 11% reduction in ATR can be achieved with a 1% cost increase. Furthermore, the existing AirClim and DOC model serve as modelling methods to evaluate atmospheric processes and direct operating costs respectively. In the case of a strategy that modifies routing and operations, parameters regarding air navigation service charges should be evaluated. And in the context of reducing emissions, emission charges should be analyzed in reference to the European Trading Scheme.

The ultimate goal of this research can be summarized as:

> "To determine the impact of operational improvements in the climate effect generated by aviation, by modelling multiple types of airlines and flight routine conditions using a dynamic programming approach ".

To elaborate on this, the research should follow a coherent structure. First, the definition of the model formulation is created, after which this is set up using Python programming language. Then the KPIs calculation is implemented, and the case study for the operational improvements is simulated. This results in a computation of the consequences for the project stakeholders and the performance of a sensitivity analysis, verification and validation.

1 Introduction

Modern society creates the need for an extensive global communications network. In the past years, the collaboration between different cultures and states has been the key to politics, art or science development. The increasing rate at which the world population requires accessibility to air transport creates the concern that improvements in aircraft technology are not happening at the speed the market growth requires.

The threat of aviation emissions relates to the radiative imbalance that they create in the atmosphere. The shift towards new equilibrium temperatures is known as climate change. The different compounds that appear as a result of fuel combustion contribute to this phenomenon in different scales and their effects vary with the location and altitude of emissions. In addition to this, the cold temperatures and humidity of the air at cruise altitudes facilitate the formation of condensation trails, which can result in the appearance of contrail cirrus clouds. On a local scale, particulate matter appearing at the engine exhaust can severely compromise the air quality of regions where flight altitudes are low. The population of communities surrounding airports experience an increase in the occurrence of cardiac and respiratory diseases. Reducing emissions and choosing optimal areas for flight routes is crucial in the mitigation of the aforementioned consequences.

To offset the increase in aviation emissions due to traffic growth, aircraft technology and its operations should be improved considerably. Development in aircraft technology revolves around efficiency improvement. Readily available modifications include the redesign of the fuselage and wing structure, this leads to enhanced aerodynamic performance, and therefore drag reduction. Moreover, research is conducted in the field of green fuels, however, the readiness level of these adjustments is not enough for a network-level implementation. Multiple airlines, such as KLM, have included the usage of bio-fuels in some of their flights [1], nevertheless, the supply availability of the aforesaid compound make it difficult for such carriers to consider the full transition. The road towards sustainable aviation ends with a transition to alternative energy sources, withal electric or solar aviation are not considered an option for the near future.

In addition to technology developments, improvement should be done in the area of airline operations. Redesigning networks and routes is key to ensure the levels of emissions are kept to a minimum. In this field is where the ClimOp project plays a crucial role, promoting operational performance enhancement in European aviation. This literature study focuses on the potential fuel consumption reduction of shorter flights, decentralized networks, low flight frequency, and changes in flight speed and altitude. The first two strategies focus on the principle of inverse snowball effect, where aircraft need to load less fuel to carry fuel by increasing the number of flight legs, reducing leg length. The low flight frequency reduces the fuel burnt per passenger by increasing aircraft size and decreasing flight frequency. Reduction in flight altitude and speed leads to a decrease in the aerodynamic drag, which ultimately minimizes fuel consumption.

The ultimate goal of the thesis study is to provide an approach to assess the different climate effect mitigation strategies. The impact of the proposed measures is evaluated with the use of modelling techniques and the establishment of key performance indicators. KPIs serve as metrics to determine economic, climate and operational impact. Due to the strategies chosen to be evaluated, special attention should be paid to parameters such as navigation and airport fees, journey duration and compromises in safety.

This report is structured as follows: Section 2 provides an outline of the different aircraft emissions and their associated atmospheric effects. Section 3 elaborates on the operational improvement strategies to be evaluated. section 6 include the environmental, economic and operational KPIs definition, and section 7 outlines impact assessment modelling techniques. Lastly, section 8 poses the research questions and summarizes the research path to be followed during the thesis phase, and section 9 concludes this report.

1.1 ClimOp: Climate Assessment of Innovative Mitigation Strategies Towards Operational Improvements in Aviation

The road towards a more sustainable aviation industry is driven by the development of new aircraft technologies, the implementation of more efficient aircraft operations, the improvement of the currently used infrastructure and the creation of a single Global Market-Based Measure to fill the remaining emission gap. IATA defines this as the 4-pillar strategy. The first pillar relies on the manufacturer's ability to improve vehicle design and develop alternative fuel compounds, with higher efficiency and lower environmental impact. The second pillar relates to potential operational improvements. The third pillar requires a compromise from the different air traffic control organisms to implement modernized ATM systems. On a market level (fourth pillar) the efforts rely on multiple parties, such as airlines and airports, to offset their corespondent emissions.

The ClimOp project represents the efforts of the European Commission to contribute to the second pillar. The main goal of this project is to propose and assess a series of operational improvements, considering their mid-to-long term (i.e. decadal) impact. The project focuses on studying the impact on the reduction of CO_2 and but also non-CO_2 effects, since the latter represent more than 50% of aviation's climate impact.

"*ClimOp will investigate, for the first time, in a sound research framework, which operational improvements actually do have a positive impact on climate, taking non CO_2 effects into account. Subsequently, it will analyse*

[1] URL https://www.klm.com/travel/nl_en/prepare_for_travel/fly_co2_neutral/all_about_sustainable_travel/biofuel.htm [cited 10 April 2020]

and propose harmonized mitigation strategies, that foster the implementation of these operational improvements. To this end, the ClimOp consortium builds on its knowledge and expertise covering the whole spectrum from aviation operations research as well as atmospheric science and consulting to airline and airport operations."[2]

2 Aviation Emissions

The different methods of transportation used in modern times are considered one of the main sources of anthropogenic pollution, representing a fifth of the greenhouse emissions in Europe [3]. Petroleum products are the source of 75% of the energy used in transportation (Dessens et al. [2014]), and, in 2018, commercial aviation was the source of 905 million tons of CO_2 emitted globally [4]. On recent years, the concern regarding aviation emissions has grown considerably, this lays in the fact that it is a rapidly growing market (3.5% more passengers per year [5]) and annual fuel efficiency improvements stay low at 1-2% (Dahlmann et al. [2016b]). Current regulations focus on the impact of CO_2 but other emissions are surrounded by uncertainty regarding limitations and taxes. According to Dahlmann et al. [2016b], the international character of this industry causes measures on a national level to be unsuccessful and to require extensive political negotiations.

2.1 Pollutant compounds

Relevant aviation emissions include: carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), water vapour (H_2O), and in smaller amounts: hydrocarbons (HC), carbon monoxide (CO) and soot. Dessens et al. [2014] classifies the aforementioned compounds in the following categories: CO_2 and water vapour, are inevitable products of the combustion of fuel; NO_x, volatile hydrocarbons and CO are dependent on the conditions of the combustion; and others, such as SO_2, are linked to fuel composition. These gases generate atmospheric perturbations that result in radiative forcing (RF) that drive the Earth towards new equilibrium temperatures, causing what we know as global warming (Egelhofer [2008]). As stated by Dahlmann et al. [2016b], maximum radiative forces are found in the tropical tropopause. Positive RF causes warming effects, and negative RF produces cooling. Not that the overall effect of aviation is difficult to assess due to the fact that different compounds act on different time frames. Schäfer and Waitz [2014] distinguishes two forms in which aviation pollution manifests itself. The first is local air quality (LAQ), which affects mainly population near airports, and the second, climate change, which has a global impact.

The impact of $C0_2$ and water vapour is related to their capacity to absorb and re-emit infrared radiation. Carbon dioxide has an atmospheric residence lifetime of 100-1000 years, and its dispersion rate is constant, which makes the location of the emissions irrelevant for quantifying purposes (see Koch et al. [2009]). On a similar note, water vapour has an atmospheric residence time of hours/months, and its impact in the troposphere is negligible due to naturally high concentrations. However, humidity levels are quite low in the stratosphere, this causes H_20 effects to be maximized for the highest flight altitudes (Egelhofer [2008]). For these reasons, water vapour and CO_2 do not influence the local air quality but are major contributors to climate change by generating a positive radiative force (warming effect).

The contribution of nitrogen oxides to climate change is defined by the altitude and geographical location of the emissions. Koch et al. [2009] describes NO_x effects as its capacity to increase ozone (O_3) concentrations and

[2] Proposal template: ClimOp, Climate Assessment of Innovative Mitigation Strategies Towards Operational Improvements in Aviation,2019

[3] URL https://www.eea.europa.eu/themes/transport [cited 8 July 2020]

[4] URL https://www.eesi.org/files/FactSheet_Climate_Impacts_Aviation_1019.pdf [cited 15 July 2020]

[5] URL https://www.iata.org/en/pressroom/pr/2018-10-24-02/ [cited 17 July 2020]

reduce the presence of methane (CH_4) in the atmosphere. These two are greenhouse gases, that produce a similar effect that CO_2, elevating the Earth's temperature. Methane and Ozone have atmospheric residence times of about 10 years and days, respectively. Even though the lower amounts of methane partially compensate for the warming effect of ozone, the total radiative force generated by NO_x is positive. Moreover, although the levels of NO_x produced by aviation are significantly low, compared to other forms of transportation, it is a bigger source of ozone production because of the altitudes at which it appears, where the radiative efficiency of this gas increases (Dessens et al. [2014]). The larger impact of ozone is observed at lower latitudes and higher altitudes.

Particulate matter (PM), such as nitrate and sulfur compounds, present a problem for climate change and also for public health. The sulfur that is present in fuels oxidizes to form sulfuric acid and aerosols, as it is explained by Dessens et al. [2014], these particles create a negative RF by reflecting solar radiation. Aerosols have the further effect of changing properties of clouds and enhancing the formation of contrails (see subsection 2.2). Sulfur oxides can cause acid rain, they have a cooling effect, however, this is of the same magnitude as the warming effects of soot, and therefore their atmospheric effects counteract each other (Egelhofer [2008]). It is important to note, that the effect of soot in LAQ cannot be neglected due to its carcinogenic nature, similar to unburned hydrocarbons and carbon monoxide, which are carcinogenic and toxic, respectively. The contribution of the latter compounds to climate change is neglected because the levels generated by aviation are significantly lower than those of other man-made activities.

2.2 Contrails

Koch et al. [2009] defines contrails as line-shaped clouds containing ice particles that form when the mixing of exhaust gases with ambient air reaches the saturation levels of liquid water. Their appearance depends on flight altitude and physical states, rather than on the amount of fuel burnt. Dahlmann et al. [2016b] states that contrails form when the air surrounding the aircraft is cold and humid (high levels of soot and sulphur oxides enhance these conditions). Wind can cause contrails to transform into cirrus clouds, and therefore changing water budget and optical characteristics of other clouds. In addition to the ones caused by the engine exhaust, the aerodynamic shape of the wing and the low pressure on the upper side can cause ice crystals to be formed and thus form contrails. Dahlmann et al. [2016b] proposes to avoid flights through ice-supersaturated regions to prevent the formation of these concentration trails.

2.3 Climate change

Different types of metrics and perspectives can be used to determine the effect of aviation emissions. Regarding climate change, the use of parameters that provide information to the general public would be the optimal quantifying form. However, as the used variables become more relevant and clear, the uncertainty surrounding their measurement increases (see Figure 1). Dessens et al. [2014] introduces two concepts: Global Warming Potential (GWP) and Global Temperature Potential (GTP). The former is the integral of the radiative forcing over a specific time interval compared to the RF created by an equal $C0_2$ mass. The latter is the ratio of temperature change produced by the compound to measure, and the temperature change produced by the same mass of CO_2. GTP provides a more relevant indicator, yet the radiative forcing (RF) is used as the reference measure for climate change despite the fact that it is not accurate as it neglects the effect location and season of the emission.

The radiative forcing generated by each of the compounds introduced in the previous section can be observed in Table 1. The effect of condensation trails and induced cirrus clouds is likewise included in the table as a further product of aviation emissions. One disadvantage of the usage of RF is its misleading interpretation of different compounds since it does not represent long-term impact, which leads to unpredictable effects. GWP presents

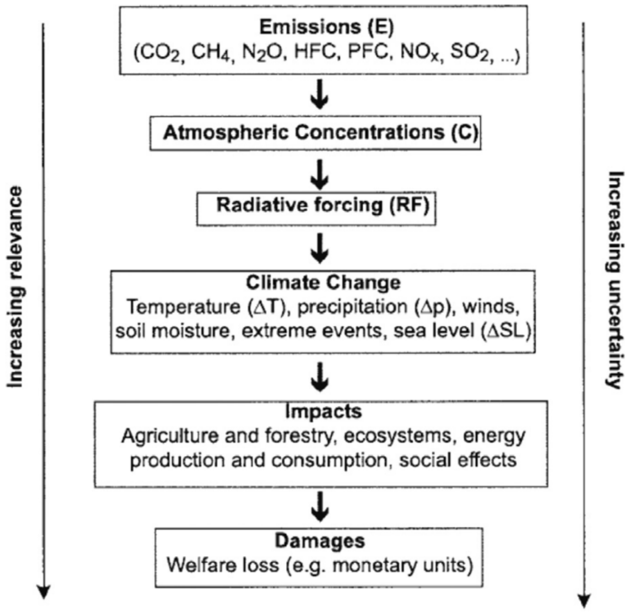

Figure 1: Cause and effect chain of the potential climate effect of emissions (from Fuglestvedt et al.)
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the same drawback, two gases with the same GWP value can produce different temperature changes if their atmospheric residence times are not equal. However, GWP is a good standard to create regulations, since it uses relevant consequences of the emissions (warming potential) as a metric. In contrast, GTP is accurate when predicting meteorological variations as a consequence of atmospheric radiation imbalance.

Table 1: Pollutant compounds or phenomena and their induced radiative forcing (RF).

Compound/phenomena	RF Magnitude	Effect
$C0_2$	28 mW/m^2	warming
O_3	26 mW/m^2	warming
CH_4	-12 mW/m^2	cooling
sulphur particles	-5 mW/m^2	cooling
soot	3 mW/m^2	warming
contrails	11 mW/m^2	warming
cirrus clouds	33 mW/m^2	warming

2.4 Local Air Quality

In addition to climate change, aviation emissions alter local air quality in areas near airports, through the increase in particulate matter concentration. These deteriorated air is the cause of respiratory and cardiac diseases and, in the most severe cases, premature death. According to Brunelle-Yeung et al. [2014], in the United States, the adult premature mortality has reached 210 deaths per year, leading to a cost of $ 1.4 billion U.S. dollars. A study performed in 310 selected airports in the continental US reveals that the concentration of particulate matter is

$2.2 \cdot 10^6 \mu g \cdot people/m^3$. Of the adverse effects, 4% is originated from different concentrations of organic PM, 12% from ammonium sulfates and sulfuric acid PM, 70% from ammonium nitrate PM, and the final 14% arise from the concentration of soot particles. Given a 10% cut in the NO_x emissions, the number of deaths a year would decrease to 199, and for a 60% cut in sulfur emissions, this number would be reduced by 39 $deaths/year$. ICAO predictions for the increase in these emissions are presented in Figure 2. Moreover, the figure shows variations in these growth rates if measures regarding ATM, infrastructure and aircraft technology are implemented in the coming years.

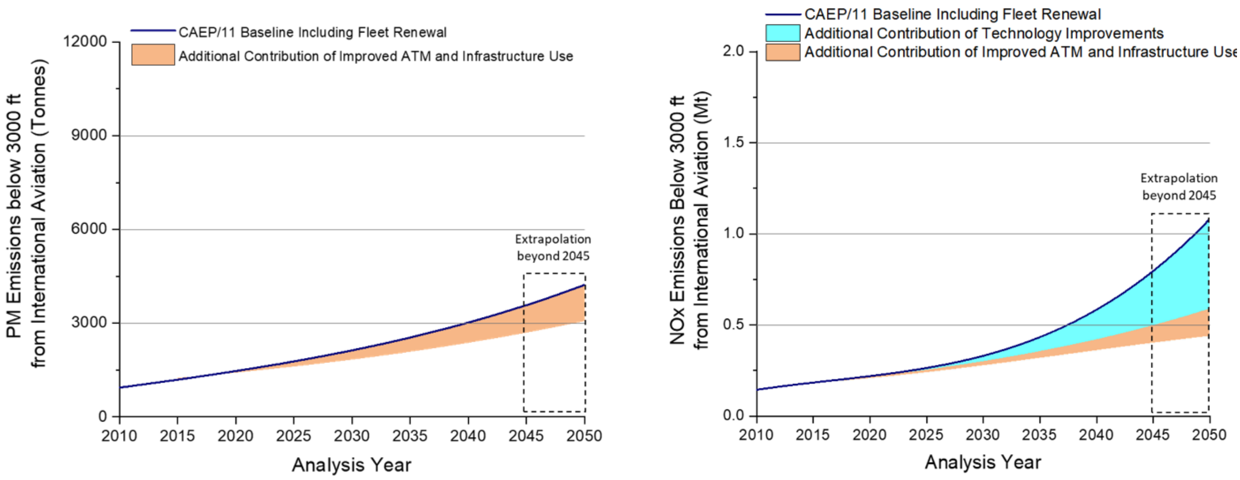

Figure 2: PM and NO_x emissions below 3,000 feet from International Aviation, 2010 to 2050[6].

3 Strategies to be tested

A series of operational improvements are proposed to evaluate the effectiveness of the assessment model. Certain strategies propose changes related to the ground operation of the vehicle, such as electric taxiing, or an optimized departure time assignment, while others focus on drastically redesigning how networks are configured nowadays, for instance, civil formation flying. The strategies suggested for testing in this section, correspond to changes which can be readily implemented in current flight planning. The upcoming subsections focus on describing, and shortly stating environmental advantages, of airline network rearrangements and flight profile redesign.

3.1 Intermediate stop operations

The implementation of Intermediate Stop Operations (ISO) consists of reducing the amount of fuel that is loaded into the aircraft by splitting the route into various legs. This strategy is proposed for long-range flights, in which a stop-over is performed to re-fuel and potentially to perform crew changes. The reduction in take-off weight results in a positive snowball effect, less fuel to carry fuel.

Linke et al. [2017] provides an analysis of the viability and consequences of including a stop in current long-haul flights. The study focuses on routes that are currently flown by wide-body aircraft, and assumes no modifications to the current fleet. Adding one extra landing/take-off influences the flight profile as seen in Figure 3. For a regular direct flight, as the amount of fuel burnt increases, the optimal flight altitude increases. In consequence of the lower initial take-off weight, the first stage of an ISO flight presents a higher altitude. The right side of the figure

[6]URL https://www.icao.int/environmental-protection/Pages/LAQ_Trends.aspx [cited 3 March 2020]

presents the relative change in emissions, the increase below cruise is due to the inefficient combustion at low thrust settings. Moreover, the increased flight altitudes of ISO intensifies the greenhouse effect of water vapour, but causes a reduction in the formation of contrails. The resultant reduction in fuel consumption is 4.8%, however, there is a significant deterioration in the LAQ (local air quality) due to the higher presence or hydrocarbons and carbon oxides.

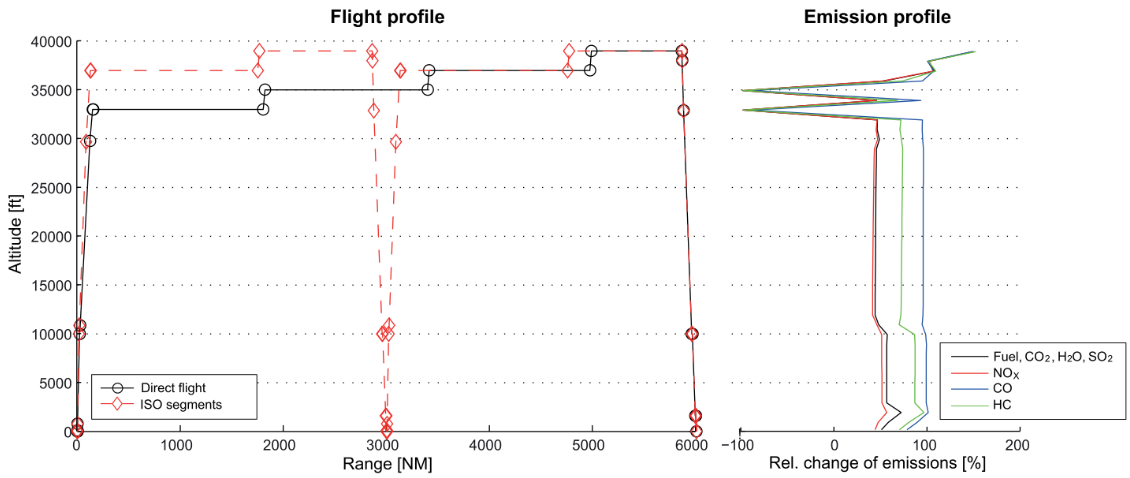

Figure 3: Change of flight altitudes and vertical emission distribution due to ISO shown on an exemplary 6000 NM mission flown with an Airbus A340-600 aircraft assuming an ideal intermediate landing (in the middle)

Linke et al. [2011] proposes to modify current medium-range aircraft to obtain maximum fuel-saving potential, for instance, optimizing the vehicle's design range (DR). Aircraft with a DR of 3000nm result in a reduction of 11.3% of the total fleet fuel consumption. Besides, the reduction in design range is beneficial for shorter flights that are still operated as direct. Nevertheless, some routes will still require to be operated by longer-range aircraft, due to the length of both legs or to the absence of suitable stop airports. Langhans et al. [2013] describes the airports in Table 2 as the optimal locations to perform the intermediate stops of current routes. Most of the world's airports that are suitable for these operations are limited in capacity, therefore, the increase in landing and take-off cycles requires modifications in the current infrastructure.

Table 2: Top 5 best located airports for intermediate stops of current flights

ICAO code	IATA code	Airport name	Country
CYQX	YQX	Gander	Canada
CYYR	YYR	Goose Bay	Canada
CYYT	YYT	St. John's	Canada
LTAR	VAS	Sivas	Turkey
PASY	SYA	Eareckson Air Station(mil.), Shemya, AK	USA

3.2 Hub-and-Spoke vs. Point-to-Point Network

Since the privatization of flag carriers, new airline business models have been developed. These models are related to the network configuration. The hub-and-spoke (HS) system is organized around a central node, from which connections are established to all destinations. On the other hand, point-to-point (PP) models provide a direct connection between all the nodes in the network. As can be seen in Figure 4, the necessary number of routes highly increase in the case of the point-to-point network. With n being the number of airports served by the airline, PP requires $n \cdot (n-1)/2$ routes, while for the same number of destinations HS only requires $n-1$ routes. HS is the model preferred for the so-called full-service carriers (FSC), while PP is mostly related to low-cost carriers (LCC). Note that modern FSC structure their operations as a "mixed multi HS" system with some PP connections.

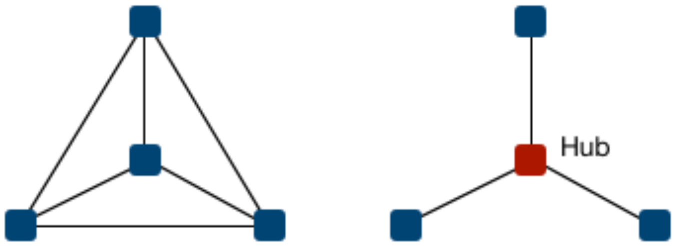

Figure 4: Point to point network versus Hub and spoke.

It is necessary to establish that PP networks are rarely an ideal configuration, and therefore not all the airports are fully connected between each other. Alderighi et al. [2007] introduces the use of the Gini and the Freeman index to analyse the spatial dimension of both configurations but chooses Freeman to be the preferred method. The Freeman index indicates centrality and takes a value of 1 for pure HS networks and a value of zero for pure PP. In agreement with Alderighi et al. [2005], HS networks seem to be spatially and temporally concentrated, as a result of the focus in optimizing the connectivity between the hubs. To improve connectivity, flights are concentrated in time frames, creating what is called "hub waves". These waves can be the cause of airport congestion and therefore delays, which is one of the main disadvantages of the HS model. Point-to-point networks are optimally used when the distance between nodes is small, when the demand for that route is small and when the total number of nodes served by the carrier is low. As it is established by, Zgodavová et al. [2018], the main advantages of the PP model are the reduction in airport dependency and the lower amount of fuel burnt and pollution created per passenger.

3.3 Trading Size for Frequency

In general aviation, the choice or aircraft size is directly linked to the length of the flight, but also to the frequency in which the route is offered to customers. Wide-body aircraft are preferred for long-haul, while narrow-body vehicles are chosen for shorter routes. The goal of most carriers is to provide high flight frequency while keeping the load factor high. To ensure this regular frequency while not incurring in extra operational costs, airlines select smaller aircraft to cover routes such as London-Amsterdam (only from Heathrow airport, this one-way route is operated 26 times per day).

Givoni and Rietveld [2010] provides an analysis of the environmental effects of fleet sizing. For comparison between narrow- and wide-body aircraft, the most commonly used type of aircraft is taken from each class, the A320-200 and the B747-400. The study focuses on analyzing disturbances in LAP (Local Air Pollution) and the global climate change caused by each vehicle. Impact on LAP is only considered during LTO (Landing Take-off) cycles, which comprise also approach and climb. In this case, the operation of the A320 (150) results in fewer emissions, during approach the LAP costs are 10% lower than those of the B747 (524 seats). However, when analyzing emissions during cruise, the B747 consumes 10% less fuel per seat when using a two-class configuration. The study of the overall flight profile outputs that larger aircraft have a lower contribution to climate change. Grampella et al. [2016] suggests that medium category aircraft have the smallest per-seat environmental costs.

3.4 Flying Lower and Slower

A reduction in flight altitude is a potential operational improvement towards cleaner aviation. Koch et al. [2009] argues that a decrease in flight level reduces the impact of nitrogen oxides and prevents the appearance of contrails. The reduction in flight altitude should be accompanied by a reduction in cruise speed, to avoid the increased drag. Current aircraft are not designed to perform under such conditions, which results in higher fuel consumption. The aforementioned article proposes several design improvements that would support the new flight conditions: high aspect ratio wings with reduced sweep, increased wing thickness, etc.

The reduction in ozone concentrations results in changes in the Sustained Global Temperature Change Potential (SGTP). The relationship between this parameter and the flight level can be observed in Figure 5. Green [2009] states that in the worst cases, a reduction of 10,000 ft in cruise altitude entails an increase in fuel burnt of 8% and a reduction in cruise speed of 7%, but a reduction of SGTP of 46%, according to values in Figure 5. If engines and aircraft are optimized to perform under these conditions, the fuel burnt penalty could be minimized.

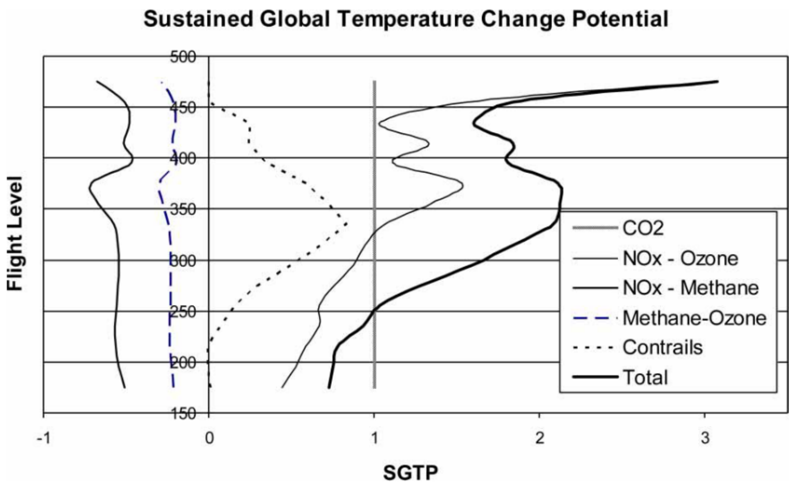

Figure 5: Variation with altitude of sustained global temperature change potential (from Green [2009])

4 Model formulation

Modern airline network modelling techniques are divided into two main approaches, linear and dynamic programming. The former is based on decisions that are all made upfront, while the latter is based on a break down of the original problem such that each of the subroutines can be solved by making one decision at a time.

4.1 Comparison between Linear and Dynamic Programming

Dreyfus [1956] describes the main differences between the linear and dynamic programming approaches. The former is presented using an intentionally simple formulation, in most cases, following the structure in Equation 1.

The latter is based on the functional relations that arise from a multi-stage decision process, which leads to the recurrence relation shown in Equation 2.

$$\text{Min.} \quad c_1x_1 + c_2x_2 + ... + c_nx_n \tag{1}$$

$$f_N(S) = max_p[R(S,P) + f_{N-1}(S'(P))] \tag{2}$$

Resource allocation problems are a typical example of dynamic programming, in which f symbolizes the return from the process carried at stage N, starting with resource S. This means that the return from stage N is a consequence of the decisions made from stage 1 to stage $N-1$. The main assumption of Linear Programming relates to the fact that it is used to model situations where the inputs and outputs of the activities, are proportional to the level of the activity. This assumption becomes invalid when dealing, for instance, with some industrial processes, where the cost of tooling or set-up is not proportional to the level of activity. In the case of a production industry, when producing zero units of type A, the associated cost is zero. However, when there are one or more units being produced, a penalty cost for set up is added regardless of the size of the batch. Dreyfus [1956] recognises a wide variety of problems where linear programming is not applicable, due to the fact that the return of a certain activity is modelled as a stochastic function of the activity level.

4.2 Dynamic Programming

Dynamic Programming relies on building sub-routines within the optimisation model, finding solutions for these sub-problems using the available information and ultimately, providing the optimal sequence of decisions that solves the overall problem. This approach reduces complexity and computation time. Powell [2011] describes the following as the minimum elements to identify in a Dynamic Programming model:

- State variable (S_1,...,S_n,...,S_N): contains the information that is required at each stage to make the next decision. It also shows the evolution of the system through the stages.
- Decision variable(x_1,...,x_n,...x_N): is the decision which moves the system from one state to the next one.
- Exogenous information (p_1,...,p_n,...,p_N): represents the information that becomes available at stage n.
- Contribution function $C_n(S_n, x_n)$: represents the contribution of the present stage to the objective function and it depends on multiple factors, such as the current state (S_n), the decision made (x_n), exogenous information (p_n) or what happens at stage $n+1$.
- Transition function $S^T(S_n, x_n)$: defines the evolution of the system from state S_n to state S_{n+1} given the decision x_n.
- Objective function $min.$ or $\underset{(x_n)_{n=1}^N}{max.}$ $\sum_{n=1}^{N} C_n(S_n, x_n)$: results in the total contribution from stages 0 to N, that is aimed to be minimized or maximized.

From this formulation, Bellman's optimality equation is derived as shown in Equation 3. Where $V_{n+1}(S_{n+1})$ represents the value of being in state S_{n+1} and γ is the discount factor arising from the fact that it refers to a future stage.

$$V_n(S_n) = \max_{(x_n \in X_t)} (C_n(S_n, a_n) + \gamma\mathbb{E}[V_{n+1}(S_{n+1})|S_n]) \tag{3}$$

5 Airline Network Modelling: The Fleet Assignment Problem

In the field of airline planning, there are two optimization problems to solve, Fleet Planning Models (FPM) and Fleet Assignment Models (FAM). Both models have profit maximization as their objective function, FPM focuses on planning the purchase, lease and sale of aircraft, while FAM creates a route assignment per aircraft operated by the airline, nowadays airlines use FAM models that also allow producing the network schedule. Since fleet renewal and planning is not relevant when analyzing the performance of current set-ups, this literature study is focused on the study of FAM. Fleet Assignment models are widely used in the airline business to conduct operations planning and can be adjusted to include constraints and considerations that are airline and network specific. In addition to the profit-maximization goal, these models aim to achieve a network capacity that minimizes the rate of spoil (seats that are left empty in a certain flight) and the number of spilled passengers (rejected due to lack of seats).

5.1 Connecting Network versus Time-Space Network

Wang [2016] defines two potential set-ups to describe the network, a connecting network, and a time-space network. The former is based on nodes that represent arrival and departure times of flights. A connection arc joins two nodes, which means that an aircraft has been assigned to the connection of two flight legs. The usage of this method is limited because it requires all the potential connections to be pre-defined. The time-space network considers the flight legs as the decision variables, and it allows for the generation of an airline schedule. In this case, the horizontal direction indicates multiple locations/stations, and the vertical separation indicates time steps (see Figure 6). Arcs of type 1 represent flight arcs, type 2 are ground arcs and type 3 are wrap-around arcs, which complete the assignment model by making it circular.

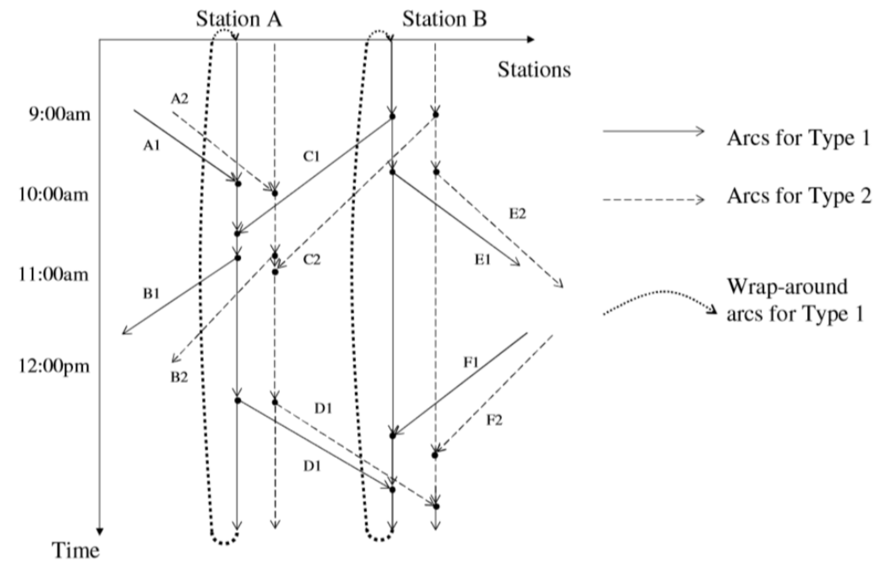

Figure 6: Time-space network, as described by Sherali et al. [2006]

5.2 Inputs for the Fleet Assignment Model

In order to model the assignment of aircraft to the routes operated by a certain airline, parameters regarding network capacity, fleet and demand, should be known. The number of seats that can be offered per flight are given by the type of the aircraft and the interior set-up chosen (single or multiple classes arrangement). Moreover, the number of seats that are offered should be adjusted according to the payload-range data of the vehicle, to be a more accurate representation of reality. Operating time is crucial to determine the availability of single aircraft, this time is defined by the block and turnaround times. Block time is defined as the period between push-back at the departure gate and the moment when the wheels are blocked upon arrival to the destination airport. Turnaround is defined as the stage that occurs since the wheels are blocked at arrival until the aircraft departs again. It is usually related proportionally to the size of the aircraft. The operating time is, at the same time, used to determine the operating costs. These costs are influenced by the utilisation rate of the aircraft and they are formed by ownership costs (interests, depreciation and insurance), fuel costs, landing, navigation and ground handling fees, and maintenance costs.

Demand

Initially, airlines have data about the number of passengers that request to travel a specific flight leg, this is known as the demand. Moreover, most of these passengers have a preference about the time of the flight, however, not all of them can be accommodated to their preferred time slot. The unconstrained demand is therefore defined as the number of passengers that should be assigned into a specific flight leg at a particular time, this accounts for passengers that had this time as their preference and passengers that had to be accommodated from other (full) time slots. Moreover, this demand should be compared to the number of seats available in the aircraft, and reduced if necessary, resulting in the constrained demand,

Since passenger demand arises from O&D routes and transfers, it is necessary to establish rules for the mixing and assignment, this is known as the passenger mix problem. The objective of this problem is to maximize the revenue per flight leg. Consider the simplified network in Figure 7.The numbers in parenthesis represent the O&D fares for each flight leg, and the amounts next to them are the unconstrained OD demands for those routes. For this example, the flight leg *A-Hub* is considered, and it is assumed that there is a single fleet type with a capacity of 100 passengers.

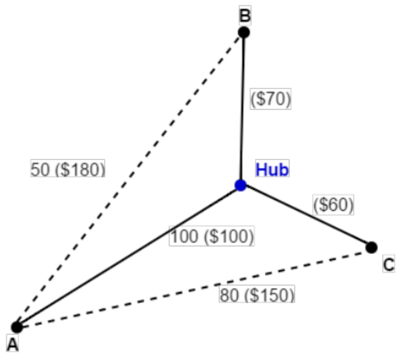

Figure 7: Example network for the passenger mix problem, from Wang [2016]

The total market demand for this flight leg is 230. Starting at Station A, 30% of the seats are reserved for local passengers, travelling to the Hub. Given the aforementioned capacity per aircraft, there are 70 remaining seats, to be distributed between passengers that are transferring to B or C. The fare applied to transfer passengers is the OD fare between their origin and destination, distributed between their two flight legs. Since transfer passengers that have flown the first leg, should be assigned a spot in the second leg, the value of the second leg is equal to that paid by local passengers, this moves the mixing problem to the first leg. Considering this, the remaining fares for the A-Hub leg are: $110 for passengers transferring to B, $90 for passengers transferring to C, and $100 for local passengers. As a result of this, the slots will be first filled with passengers transferring to B. Since the demand does not meet the capacity, the seats will be subsequently filled with local passengers, who pay a higher fee than those transferring to C. The final result is that, for the leg A-Hub, which has 100 slots, 50 will be taken by local passengers, and 50 by passengers transferring to B. In summary, the passenger mix is obtained by adding passengers from the highest-paid fare, on-top of the 30% reserved local passengers, until the capacity of the aircraft is met. Note that for transfer passengers to be assigned to a connecting flight, there should be a 30 minute time buffer between the arrival time and the departure of the second flight.

5.3 Fleet Assignment using Linear Programming

Hane et al. [1995] introduces a basic mathematical model that would serve as a basis for future work. C denotes the set of cities served, F is the set of available fleets, the number of aircraft in each fleet is $S(f)$ for $f \in F$. The set of flight is denoted by L, with elements i or $\{odt\}$ being $o, d \in C$ and t the time. Marketing constraints require that certain flights that are more profitable as one-stop service are operated as such, these flights are known as "required throughs". The set of required throughs is represented by H. Nodes N in the network are identified by $\{fot\}$ with $f \in F$, $o \in C$ and t time of take-off or landing at o, being the last node $\{fot_n\}$ and the first one $\{fot_1\}$. The decision variable X_fodt (also denoted as X_fi) takes the value 1 if fleet f is assigned to the route from o to d, departing at time t, and takes the value 0 otherwise. Moreover, there are variables Y_fott^+, which represent the ground arcs, being the time interval, (t, t^+), the period the aircraft remains grounded. With the goal of minimizing the operational cost, the mathematical model is as follows:

$$\text{Minimize} \sum_{i \in L} \sum_{f \in F} c_{fi} X_{fi} \tag{4}$$

Subject to:

$$\sum_{f} X_{fi} = 1 \qquad \text{for all } i \in L \tag{5}$$

$$\sum_{d} X_{fdot} + Y_{fot^-t} - \sum_{d} X_{fodt} - Y_{fott^+} = 0 \qquad \text{for all } \{fot\} \in N \tag{6}$$

$$X_{fi} - X_{fj} = 0 \qquad \text{for all } (i,j) \in H \tag{7}$$

$$\sum_{i \in O(f)} X_{fi} + \sum_{o \in C} Y_{fot_n t_1} \leq S(f) \qquad \text{for all } f \in F \tag{8}$$

$$Y_{fott^+} \geq 0 \qquad \text{for all } \{fott^+\} \in N \tag{9}$$

$$X_{fi} \in \{0,1\} \qquad \text{for all } i \in L \text{ and } f \in F \tag{10}$$

Equation 5 is a constraint that ensures each flight leg to be flown by the same fleet, Equation 6 is the flow balance constraint, which guarantees that the flow is conserved and circular. In addition, Equation 7 enforces that for the required through, the flight legs are flown by the same fleet. Equation 8 is added to make sure that, at a certain point in time, the total number of aircraft equals the number of aircraft flying, plus the number of aircraft on the ground.

Faber [2017] uses a similar approach, but adapting it to model the influence of the European Emission Trading Scheme (EU-ETS). This results in the following assumptions being added to the Hane et al. [1995] model:

Assumption 1: Operation costs can be modelled with maintenance and fuel costs.

Assumption 2: No through flights.

Assumption 3: Single aircraft assignment can be changed to sub-fleet assignment without affecting the assignment results.

Assumption 4: All aircraft will return to a hub within the assignment time span.

Assumption 5: The pilot costs are not influenced by the aircraft type.

Assumption 6: The difference in cabin crew cost per passenger between aircraft types can be neglected.

Assumption 7: All EU emission allowances (EUA) have to be bought.

Assumption 8: The fuel emitted in the EU airspace can be computed with the selected waypoints.

Assumption 9: The route distance can be approximated by the shortest distance from origin to destination with an addition of 10%.

Certain assumptions of this list are not valid for the analysis of the operational improvements proposed in section 3, for instance, in order to assess the impact of ISO, through flights should be included in the model. Moreover, charges such as landing fees and crew salaries should be included in the operating cost calculation, to account for the savings or increased expenses arising from the aforementioned strategies. In addition to these assumptions, Faber [2017] model uses bigger time steps, since single aircraft assignment is not relevant for the research. This causes the previously mentioned total aircraft conservation constraint (Equation 8) to not be valid. Instead, it is replaced by a constraint that maintains a balance on the utilisation hours of the aircraft: the total number of aircraft owned are multiplied by the aircraft utilisation and compared to flight hours and turnaround times.

5.4 Dynamic Programming

For the purpose of airline scheduling, Hersh [1974] presents a heuristic approach that continues the research of the basis of dynamic programming, applying the theory to the airline planning problem through four major stages:

1. Generation of feasible routes.
2. Sequential assignment of aircraft routing.
3. Passenger assignment and network evaluation.
4. Sequential reassignment of routings to achieve improved performance.

Step 1 is performed only once, the following steps are run repeatedly until no significant improvement in profit is made. The general approach followed by this model can be observed in Figure 8. Passenger priority is defined by the number of stops and changes of aircraft during the journey. Woudenberg [2019] adapts the dynamic programming scheme intended for fleet planning purposes, it introduces the decomposition of the scheduling problem based on individual aircraft. This means that a certain aircraft will be assigned to a specific route in this point of time if that results in the optimal route combination at the end of the studied period. This model requires fleet, network and market characteristics as its inputs, and it runs based on aircraft availability. Certain constraints are imposed on aircraft level, and therefore, they can be evaluated inside the subroutines, others are related to the global system, and should be analysed when the complete schedule is produced.

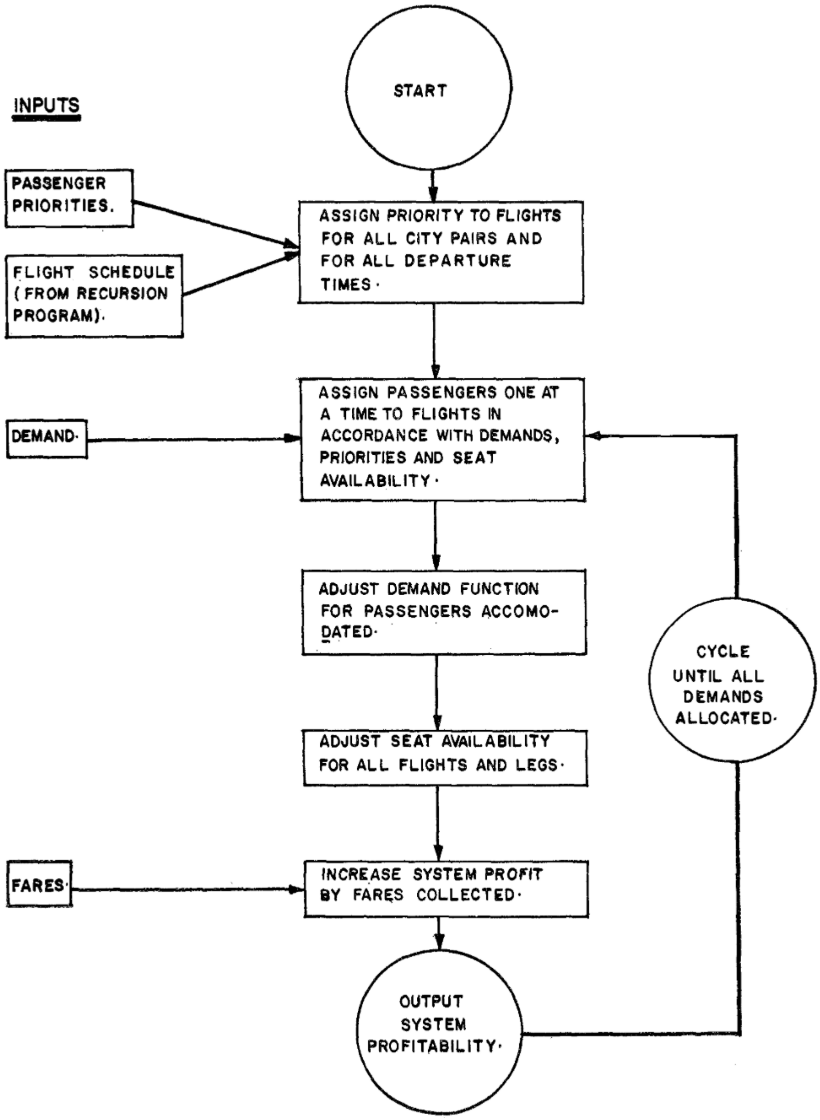

Figure 8: Passenger allocation program as designed by Hersh [1974]

Wang [2016] defines this approach as a decomposition of the fleet assignment problem into 2 levels of dynamic programming. On the first level, the aircraft are sequentially added to the problem, such that individual optimal schedules and routes are found before new aircraft are added. On the second level, the aircraft sub-problem is divided into the different time steps. This approach presents the problem that past decisions cannot be changed once new information is added, this can be the source of a final solution that is not globally optimal.

The problem formulation of the model presented by Wang [2016] for the fleet assignment optimization of one aircraft includes the following:

Sets

S: set of cities, or stations, indexed by i, k or h
J: sets of fleet types, indexed by j
L: set of possible flights, indexed by l or ik

T: set of event times at all stations, indexed by t
N: set of nodes in the time-space network, indexed by jit

Decision Variables

$$f_{j,l} := \begin{cases} 1 & \text{if flight l} \in \text{L is assigned to fleet type j} \in \text{J} \\ 0 & \text{otherwise} \end{cases}$$

y_{jit^-}: number of aircraft of fleet type $j \in J$ at station $i \in S$ immediately before time $t \in T$
y_{jit^+} : number of aircraft of fleet type $j \in J$ at station $i \in S$ immediately after time $t \in T$
$x_{\{ik\}}$: direct passenger flow from stations i to k and $\{ik\} \in L$
$u_{\{ih\}}$: transfer passenger flow from spoke i to hub h and $\{ih\} \in L$
$w_{\{hk\}}$: transfer passenger flow from hub h to spoke k originating from i and $\{hk\} \in L$

Parameters

$profit_{j,l,t}$: profit earned on flight leg $l \in L$ flown by fleet type $i \in J$ departing at time $t \in T$
$bt_{j,l}$: block time of fleet type $j \in J$ on flight $l \in L$
$UT_{min,j}$: minimum daily utilization in hours for fleet type $j \in J$
$UT_{max,j}$: maximum daily utilization in hours for fleet type $j \in J$
$UDemand_{\{ik\}}$: unconstrained demand on flight $\{ik\} \in L$
Cap_j : available capacity on fleet type $j \in J$

The mathematical formulation is presented below.

$$\text{Max} \sum_{l \in L} \sum_{j \in J} profit_{j,l} \times f_{j,l} \tag{11}$$

subject to:

$$\sum_{j \in J} f_{j,l} \leq 1 \qquad \forall l \in L \tag{12}$$

$$y_{jit^-} + \sum_{l \in I(jit)} f_{j,l} - y_{jit^+} - \sum_{l \in O(jit)} f_{j,l} = 0 \qquad \forall jit \in N \tag{13}$$

$$UT_{min,j} \leq \sum_{l \in L} f_{j,l} \times bt_{j,l} \geq UT_{max,j} \qquad \forall j \in J \tag{14}$$

$$u_{\{ih\}} = \sum_{k \in S} w^i_{\{hk\}} \qquad \forall i \in S \tag{15}$$

$$x_{\{ik\}} + w^i_{\{hk\}} \leq UDemand_{\{ik\}} \qquad \forall \{ik\} \in L \tag{16}$$

$$\sum_{\{ik\} \in L} f_{j,\{ik\}} \times (x_{\{ik\}} + \sum_{h \in S} w^h_{\{ik\}}) \leq UDemand_{\{ik\}} \qquad \forall \{ik\} \in L \tag{17}$$

Equation 11 represents the objective function of the optimization problem, which entails profit maximization. Constraint 12 is the cover constraint, which ensures that each flight is covered by a single aircraft. Constraint 13 is the flow conservation constraint, to maintain the balance between aircraft in and out of the station. Constraint 14 considers that each fleet type is used according to its limit utilization rates. Constraint 15 ensures connectivity by making sure that transfer passengers flying to the hub are also assigned a flight out of it. Constraint 16 sets the total maximum passengers to be served to be smaller than the demand. And finally, constraint 17 sets the maximum number of passengers to be served to be smaller than the available capacity.

6 Key Performance Indicator Definition

To build a model that correctly evaluates the impact of climate mitigation strategies, it is required to establish a series of key performance indicators (KPIs). These define which parameters are considered relevant to decide which measures should be ultimately implemented. In addition to the evident environmental metrics, economic effects of the operational changes should be considered, as well as the effect on airline operations indicators. Furthermore, it is appropriate to consider changes in the safety of flights, no measures should be adopted if they present a threat to passenger and crew safety.

6.1 Environmental Key Performance Indicators

The goal of this study is to establish assessment criteria for operational improvements that reduce the environmental impact of aviation. section 2 outlines the different pollutant compounds and elaborates on their different contributions to local air quality and climate change. The ultimate effect of emissions can be summarized with the use of the following metrics:

- **Fuel burnt**, the main pollutant agent of aviation is carbon dioxide (CO_2), and its emission levels are directly proportional to the amount of fuel burnt.
- **ATR**, the average temperature response is the mean temperature change in the Earth's surface over a given time horizon (see Equation 18). Regularly time horizons of 20 and 50 years are used.

$$ATR_H = \frac{1}{H} \int_t^{t+H} dT(t)dt \tag{18}$$

- **Local Air Quality Fluctuation Index**, changes in this metric result in the increased appearance of cardiac and respiratory diseases in the population surrounding airports. Monitoring this parameter is therefore required in an environmental impact assessment.

6.2 Economic Key Performance Indicators

The goal of economic KPIs is to assess the financial impact of the proposed strategies. In addition to cost savings/increase due to re-routing or changes in fuel consumption, the change in environmental impact leads to savings in the budget for emission charges. Before defining the chosen economic KPIs, it is left to specify the following concepts:

- **ASK**, available seat kilometer, serves as a measure of the capacity offered and the distance travelled by an airline.
- **RPK**, revenue passenger kilometer, similar to ASK, however it measures the number of passengers transported rather than the capacity available.

- **ATK**, available tonnes kilometer, cargo equivalent of ASK.
- **FTK**, freight tonnes kilometer, cargo equivalent of RPK.

In order to evaluate the cost fluctuations, the aforementioned metrics are related to their associated money flows, resulting in the following KPIs:

- **RASK**, revenue per ASK, assesses the operational revenue resulting from each ASK supplied.
- **CASK**, cost per AKS, is a metric of the operational cost generated by each ASK supplied.
- **Yield** is the revenue gathered per RPK handled.

Note that similar to commercial flights, these indicators can be applied to cargo flights. The goal of the airline is to maximize revenue while minimizing costs, that is to obtain the maximum operating profit, calculated as follows:

$$\textbf{Operating Profit} = \text{Operational Revenue} - \text{Operational Costs} \tag{19}$$

$$\textbf{Operating Profit} = \text{RPF} \times \text{Yield} - \text{ASK} \times \text{CASK} \tag{20}$$

Changes in an airlines profitability are estimated using methods to determine the direct operating costs (see subsection 7.3).

6.3 Operations Based Key Performance Indicators

Given the improved strategies proposed in section 3, certain aspects of an airline's normal operations can be affected. Reducing the number of legs in one flight, or increasing travel duration, can have as a consequence positive and negative variations of the following performance indicators:

- **Aircraft Productivity**, is the average number of ASK for a specific time period. In the case of implementing measures such as ISO, aircraft productivity could decrease significantly as a result of the increase in block hours.
- **LTO cycles**, (Landing and Take-Off cycles), serves as an indication of the utilisation of the aircraft systems.
- **Routing Efficiency**, measurement of the difference between the proposed optimised route and the original path.
- **OTP**, on-time performance, indicates the percentage of flights that are performed with less than 15 minutes delay. Introducing more flight legs, results in extra airport operations, which can introduce delays.
- **Extra Travel Time**, emerging from the added flight duration due to slower flights or extra stops.
- **Network Capacity**, measured with the above-mentioned terms ASK and ATK.
- **Load Factor**, is the portion of the available capacity within the network that is being used. It can be computed dividing the Revenue Passenger Kilometer (RPK) by the Available Seat Kilometer (ASK).

6.4 Safety Key Performance Indicators

Every flight phase has an associated risk factor, this probability of failure increases during take-off and landing. Zaporozhets and Gosudarska [2016] states that 82.06% of the total aircraft accidents happen during these flight phases. Therefore, since some strategies propose the introduction of extra stops on the flight, it is necessary to establish a safety assessment within the KPI definition. The Safety Assessment Methodology (SAM) proposed by EUROCONTROL is a tool that analyzes the risks associated with air transport systems. It consists of three steps: Functional Hazard Assessment (FHA), Preliminary System Safety Assessment (PSSA) and System Safety Assessment (SSA). Through these, multiple threats are identified and quantified. These threats include: Mid-air collisions, which are studied based on the frequency of occurrence per flight hour; taxiway or runway collisions and flight into terrain accidents, measured on a per-flight/movement basis; etc.[7].

7 Impact Assessment

Evaluating the metrics proposed in section 6 is done by establishing models that calculate outputs for the different parameters. The German Aerospace Center (DLR) developed the CATS model that includes environmental and economic impact assessment. Climate effects are assessed with the use of the AirClim model to linearize atmospheric processes. However, the sources used for direct operating costs calculation should be varied accordingly to European or airline-specific data, and completed by considering the impact of emission charges.

7.1 Climate Compatible Air Transport System Model

Dahlmann et al. [2016b] summarizes the CATS project, conducted by DLR (German Aerospace Center) between the years 2008 and 2012. This project focuses on obtaining climate effect reduction potential for current aircraft versus climate-optimized future vehicles. The model outputs are evaluated based on emissions and economic impact, the former is assessed using the AirClim model to calculate average temperature responses (see subsection 7.2, while the later is evaluated through the calculation of the resultant cash operating costs (COC), which includes fuel, crew and maintenance costs, in addition to landing and navigation fees (see subsection 7.3).

The model has as its main goal to look for the most cost-efficient strategies by simulating for each route (i), multiple trajectories (k) as a result of changes in the flight conditions. For every output, COC and ATR are evaluated relative to the reference trajectory values per route (see Equation 21 and 22).

$$COC_{rel,i,k} = \frac{COC_{i,k}}{COC_{i,ref}} \tag{21}$$

$$ATR_{rel,i,k} = \frac{ATR_{i,k}}{ATR_{i,ref}} \tag{22}$$

From the ratio of ATR versus COC, a Pareto front is obtained that optimizes the combinations of flight conditions. Note that mitigation potential is given at discrete values due to the loss of information arising from interpolation. The research group chooses the A330-200 as a reference aircraft for this study since it is an example of high sales middle to long-range aircraft. In the year 2006, this vehicle was assigned to 1178 routes worldwide. The results of the study show a great climate effect reduction potential, with a low cost increase. A 42% ATR reduction would lead to a 10% COC increase, while a 11% ATR reduction can be achieved with a COC increase of 1%. The CATS project continues to develop optimized aircraft design characteristics to maximize the climate impact mitigation potential.

[7] Tud, B. F. S., Tud, F. Y., Tud, P. R., & Dlr, F. L. (n.d.). D1 . 1 – Definition of climate and performance metrics. 1–37.

7.2 AirClim Model

Grewe and Stenke [2008] propose the AirClim model as a linearization of atmospheric processes that provides an accurate indication of the environmental impact of aviation. As opposed to other imprecise metrics such as fuel burnt, this model is based on the calculation of near-surface temperature changes. Forster et al. [2006] summarizes a series of requirements for the "appropriate metric", however, consensus on what is the most suitable has not been achieved yet. The AirClim model ignores historical data and has as its inputs aircraft emission data (3D), precalculated atmospheric data and background data on the evolution of emissions. For a more detailed outline on these inputs see Figure 9.

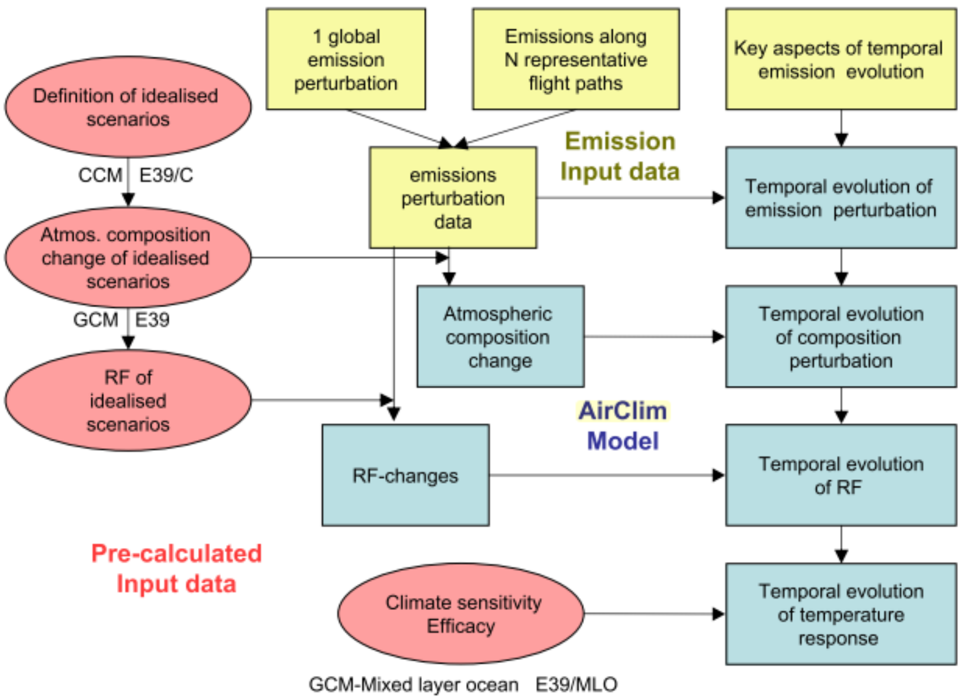

Figure 9: Overview of the multi-step approach to derive near surface temperature changes and ozone depletion from emission scenarios (from Grewe and Stenke [2008]).

The pre-calculated input data consists of radiative forcing calculations using the chemistry model E39/C. The RF is obtained based on chemical perturbations of the pollutant compounds, and it is calculated for different emission regions. These regions are defined by varying latitudes to account for the difference in the impact of multiple geographic locations, and, besides, it accounts for supersonic cruise levels or subsonic air traffic. Each of the areas is characterised by a standard mixing ratio over time. External effects such as emissions from industries or transportation are accounted for using predictions for the year 2050. The model output is computed for the year 2050 and calculated for the following 5 years to obtain annual rates.

The AirClim model is established to provide a comparison between aircraft technologies and therefore multiple data sets are required: the base scenario and the two potential improvements to be compared. CO_2 emissions are accounted for by integrating emissions along the flight paths. For other emissions, realistic values are obtained by combining pre-calculated emissions and the temporal evolution of each compound, which is given by its chemical nature.

Variables such as climate sensitivity or the lifetime of compounds are obtained through models that introduce uncertainty in the AirClim simulation. This uncertainty is not statistical, but arises from the different modelling techniques that exist for climate effects, and due to its computational complexity, uncertainty calculations are not included in the model. The errors in the model are statistically dependant and therefore, Dahlmann et al. [2016a] suggest a Monte Carlo simulation as the assessment method. To reduce running times, the MC simulation is introduced in the AirClim model, rather than run repeatedly for each simulation. This study concludes that, although the results in temperature changes belong to wide ranges, on emission level it is a reliable indicator of the adequacy of the evaluated aircraft technology.

7.3 Direct Operating Cost Model

The DOC model is proposed by Liebeck et al. [1995] to estimate the "direct operating costs" associated with individual flights. Note that this method is developed by NASA and therefore some of the parameters should be adjusted accordingly to European values. This economic study divides operating charges into cash and ownership costs. The former are expenses associated with the day-to-day aircraft operation, while the latter are related to the purchase of the vehicle.

Cash costs (COC) include cockpit crew prices, obtained based on maximum take-off gross weight (MTOGW); cabin crew prices, relative to the number of seats in the aircraft; landing and navigation fees, calculated from maximum landing gross weight (MLGW) or MTOGW; and fuel costs which are derived from the price per gallon and mission block fuel. In addition, maintenance costs are also included in the COC, and they are formed by labour, material and burden costs; these quantities are calculated based on airframe weight, flight cycle and flight hour. Furthermore, engine maintenance costs should be obtained from the engine manufacturer. Ownership costs are divided into depreciation costs, based on the total aircraft price and the associated spares prices; interest fees, since most aircraft purchases are funded through long-term debt; and finally, insurance costs which usually are established at a rate that is 0.35% of the total airplane price.

7.4 Air Navigation Service Charges

Alterations in common aircraft routing such as ISO are a source for changes in Air Navigation Service (ANS) costs, these fees represented 9% of the direct operating costs of members of the Association of European Airlines(AEA) in 2005. Castelli and Ranieri [2007] divides navigation charges into en-route and airport charges.The total en-route charge per flight, R, is obtained as follows:

$$R = \sum_{i=1}^{n} r_i \tag{23}$$

The national charge r_i is the product of the distance factor d_i, the national unit rate t_i and the weight factor p, which is equal to $\sqrt{\frac{MTOW}{50}}$. National unit rates are calculated each year for the following one based on the forecast of en-route services cost, and the forecast en-route service units. For most countries, the unit rate varies with staff costs and airspace complexity, and it obeys the principle of break-even, revenue matches the costs. Terminal charges (TC) are less standardized than general en-route services, and therefore the high discrepancy in its values. The general formula to obtain TC values is the product of the terminal unit rate and the weight factor, the latter calculated from $(\frac{MTOW}{50})^{0.7}$. This system leads to high dissimilarity in route and terminal charges, which results in inefficient aircraft routing, where aircraft fly longer but cheaper routes. Currently, research is being performed regarding the implementation of "Single European Sky", which would solve the contrast problem between the multiple ANS providers.

7.5 Emission Charges

Since the year 2012, aviation emissions have been a part of the European Trading Scheme (ETS), which means that all flights departing from, or arriving, to Europe are required to monitor and report their emissions. Carriers are assigned tradeable CO_2 allowances every year, and to include other compounds, equivalences should be established between their effect and CO_2 effects. In Europe, charges on local NO_x and hydrocarbons have been applied since the 1990s. However, this relates in its majority to emissions during take-off and landing, phases in which such compounds represent considerable threats to local air quality.

Scheelhaase et al. [2016] present the AviClim model to assess the aviation impact from an economic point of view. This model proposes four scenarios to be evaluated, scenario 1 includes the Greater EU area, which is formed by the territories currently affected by the EU ETS; scenario 2 comprises the Greater Aviation Countries, which account for 90% of the world's air traffic; scenario 3 is formed by the Annex-I countries, those that signed the Kyoto protocol in 1997, plus BRIC countries (Brazil, Russia, India and China); lastly, scenario 4 is denoted as World and involves all countries. In order to balance economic efficiency with environmental savings, the model studies all four scenarios under the following market-based measures: emission trading scheme that regulates relevant emissions, climate taxes for all relevant emissions, and an NO_x emission charge combined with a CO_2 trading scheme and operational measures (such as reduce flight altitude to avoid contrail formation). This model assumes that the accountable entities are the airlines. See Figure 10 for a diagram of the AviClim approach.

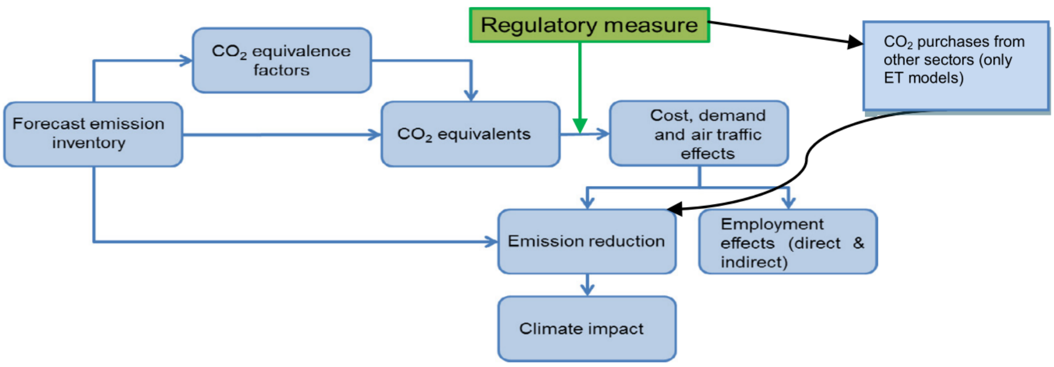

Figure 10: Schematic of the AviClim modelling approach (from Scheelhaase et al. [2016])

The main conclusion of this model is that the optimal scenario is to apply a global scale strategy, this could lead to a 70% reduction in climate change impact by the year 2100. Nevertheless, the results from scenario 2 and 3, are close to optimal, since most of the world's air traffic is originated from countries which also belong to these two categories.

The inclusion of aviation emissions in the European Trading Scheme has resulted in a carbon footprint reduction of 17 million tonnes per year [8]. Between the years 2013 and 2017 carbon allowance prices ranged between €4 and €6 per tonne, which is translated into an increase from €89 million (in 2013) to €189 million (in 2017) in costs for aircraft operators (see EASA [2019]). In September of 2018, the allowances were being traded at €20 per

[8]URL https://ec.europa.eu/clima/policies/transport/aviation_entab-0-0 [cited 10 March 2020]

tonne of CO_2. In the year 2016, ICAO announced their intention to create a global regulation system for CO_2 emissions, to be applied in the year 2021.

8 Research Questions and Approach

This section focuses on describing which knowledge gap the thesis research aims to fill. Current models and estimations include considerations of average temperature response and effects on direct operating costs. However, they are missing to identify effects on local air quality and other non-economical KPIs, such as safety implications or operations impact. Moreover, the strategies proposed in previous sections require a flexible approach that can be adapted to fit varying airline business and flight conditions.

8.1 Research Question

Due to the aforementioned gaps in state-of-the-art techniques, the following research questions are proposed:

- How to effectively model multiple airline network set-ups and trajectory constraints in order to determine the climate impact of diverse operational improvements?
  - What is the most suitable modelling framework?
  - What are the relevant airline operations aspects to model?
  - Which set of constraints should be included in the model?
  - What are the relevant metrics to evaluate strategy impact?
- What is the stakeholder impact of the proposed operational improvements?

8.2 Research Objective

The goal of this project consists of providing a model which supports being adapted for multiple airline business models, namely, point-to-point versus hub-and-spoke networks. In addition, this model should be suitable for the introduction of intermediate stops in the flights, and for the modification of flight characteristics, such as flight speed.

The main research objective of this thesis is:

> "To determine the impact of operational improvements in the climate effect generated by aviation, by modelling multiple types of airlines and flight routine conditions using a dynamic programming approach ".

The first step in order to complete the main objective is to develop a fleet assignment and network schedule model, which can simulate real airline set-ups. Furthermore, the conditions for each of the operational improvements are included, such that current flight characteristics can be modified. Finally, a series of key performance indicators (KPI) should be implemented in the calculations to assess the suitability of the strategies proposed.

8.3 Project approach

In the aim of developing the appropriate model and provide relevant results, the upcoming phases of this project should focus on modelling the strategies and studying the assessment of the KPIs. To do so, the research should follow a coherent structure and build upon the knowledge gained at each step. The methodology proposed for the thesis research phase is as follows:

1. Familiarisation with network modelling techniques.
2. Definition of model inputs and outputs
3. Definition of model constraints
4. Set up network model with dynamic programming for the fleet assignment.
5. Development of the assessment technique and implementation of KPIs.
6. Simulation of the ClimOp case study.
7. Computation of consequences for the Stakeholders.
8. Sensitivity analysis focusing on the uncertainty of emissions modelling.
9. Verification and Validation.

The tool chosen to complete these tasks is the programming language Python. The main goal is to create a model that can be easily adaptable to test multiple operational improvements, and provide an indication of the potential environmental advantages. The general flow of the research can be observed in Appendix A.

8.3.1 The Dynamic Programming Framework

Fleet assignment problems are solved using dynamic programming in a similar form to shortest path problems. The goal is to determine the sequence of decisions that, in this case, maximizes profit for the airline (instead of distance minimization in the shortest path problem. To illustrate this concept, a simple set-up is presented in Figure 11. Airline X has an aircraft of type A, which should be assigned a certain route to follow in a day, given that it should end at the hub. The hub (Amsterdam) is connected to the cities of London, Paris and New York; in addition, the cities of Paris and London are also connected to New York. The optimal result is a combination of flights between the stations and stops at them. Based on the demand for these routes and the associated costs, profits are assigned to the different decisions, travelling between two cities, or remaining at one. A summary of these can be seen in Table 3.

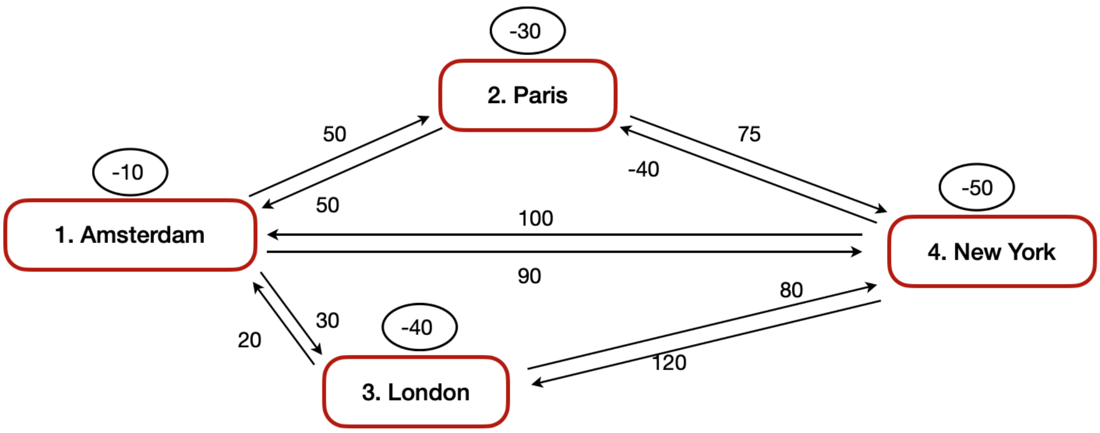

Figure 11: Set-up for the simplified dynamic programming example

The notation of this problem includes the *state* (s_i), station at stage i. Considering that one day is divided into four time steps (4 stages), and that the time spent to travel from one station to the other is exactly one time step, the decision variable x_i consists on deciding what the next state is for aircraft A. The profit at stage i, given

Table 3: Summary of the route-associated profit.

	Amsterdam	**Paris**	**London**	**New York**
Amsterdam	-10	50	30	90
Paris	50	-30	0	75
London	20	0	-40	80
New York	100	-40	120	-50

decision x and state s, is denoted as $f_i(s,x)$. The decision that maximizes this profit is denoted as x_i^*, and the associated maximum value of the profit is $f_i^*(s)$.

To follow the dynamic programming logic, the first step is to analyze stage 3 ($n = 3$), since we know that state 4 is Amsterdam. This situation is summarized as:

	$f_3(s_3, x_3)$		
s_3\x3	Amsterdam	$f_3^*(s_3)$	x_3^*
Amsterdam	-10	-10	Amsterdam
Paris	50	50	Amsterdam
London	20	20	Amsterdam
New York	100	100	Amsterdam

When adding new stages, the profit from the optimal upcoming solution should be added to the profit per decision. For stage 2 this means, that on top of the profit generated by the flight in stage 2, f_3^* should be added to the profit per decision:

	$f_2(s_2, x_2)$	$f_2(s_2, x_2)$	$f_2(s_2, x_2)$	$f_2(s_2, x_2)$		
s_2\x2	Amsterdam	Paris	London	New York	$f_2^*(s_2)$	x_2^*
Amsterdam	-20	100	50	190	190	New York
Paris	40	20	0	175	175	New York
London	10	0	-20	180	180	New York
New York	90	10	140	50	140	London

And finally, stage 1 ($n = 1$):

	$f_1(s_1, x_1)$	$f_1(s_1, x_1)$	$f_1(s_1, x_1)$	$f_1(s_1, x_1)$		
s_1\x1	Amsterdam	Paris	London	New York	$f_1^*(s_1)$	x_1^*
Amsterdam	180	225	210	230	230	New York
Paris	240	145	0	215	240	Amsterdam
London	210	0	140	220	220	New York
New York	290	135	300	90	300	London

Given that the aircraft should start the process at the Hub Amsterdam, the station combination that maximizes profit is: Amsterdam - New York - London- Amsterdam. This process is then repeated for all the aircraft in the fleet of airline X. For this research, the goal is to introduce a time horizon of one week, assuming that the schedule will repeat every seven days.

9 Conclusion

The goal of this literature study is to serve as a basis for the research regarding the potential environmental savings of operational improvements in the aviation section. The research is based on building a model that can simulate multiple airline operations aspects. The model should support the introduction of the chosen operational improvements for testing. The first strategy to test is the introduction of multiple stop operations, which is based on reducing the amount of fuel to be loaded into the aircraft by splitting flights into multiple legs. Previous studies show that for range-optimized aircraft, the fuel reduction potential is of up to 11.3%. The second strategy is the switch between Hub-and-Spoke to Point-to-Point networks. HS arrangements correspond to airlines which organize their flights around a central node, that is then connected to all the destination nodes. PP networks are formed by direct connections between all the nodes in the network. Normally this type of arrangement is used by Low Cost Carriers. The third strategy consists of reducing flight frequency between certain airports and increasing the size of the aircraft that cover the route. It has been proved that medium-size aircraft have the smallest environmental impact per seat. Finally, the fourth strategy relates to reducing flight altitude and speed. Lower flight levels are associated with a lower NO_x impact and a decrease in the formation of contrails. To avoid the increase in drag, the flight speed should be reduced accordingly.

Optimization problems such as those involved in airline planning can be solved via two approaches: linear and dynamic programming. The former is based on a proportional relation between the inputs and outputs of the model and the level of activity. The latter uses a multi-stage decision process that allows reducing complexity and computational time. For this specific problem, dynamic programming is the chosen framework due to its ability to output a network schedule as well as a solution for the fleet assignment problem, using profit maximization as the objective function. The basis of dynamic programming lays on Bellman's optimality equation, which establishes the value of a state based on current decisions and the outcome of decisions from future stages. The problem is divided into two levels, on the deeper level each aircraft is assigned a movement per time step, on the higher level aircraft are successively added to the network, until the entire fleet is considered. The time/space assignment is achieved by modelling a time-space network. The inputs of the model fall into three categories: fleet characteristics, demand and network capacity. The demand should be adapted to capacity by obtaining constrained demand. Moreover, the Passenger Mix Problem should be considered to account for local and transfer passengers. As it was mentioned before, the objective function for this optimization routine is the profit maximization for the airline. The model is completed by adding constraints. Firstly, the cover constraint ensures that each flight is assigned one and only one aircraft. The second constraint is the flow conservation constraint, which regulates the flow in and out of one airport. Besides, constraints should be added to ensure connectivity, to limit utilisation of the vehicles and to restrict the seats served under the demand and capacity levels.

After the operational improvements are modelled, it is necessary to define Key Performance Indicators to assess their performance. These KPIs are related to environmental, economic, operational and safety conditions. By providing results on the impact of the strategies on the mentioned fields, advice can be generated about the suitability of its implementation. Given this, the research objective lays on creating a dynamic programming model to determine the impact of operational improvements in the climate effect generated by aviation.

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III

Supporting Material

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1
Original Alitalia Schedule

The following schedule is used to create demand used as input for the model. Note that all the times are in the model time zone and not in the location time zone.

Table 1.1: Original Alitalia Schedule for Monday.

Day	Departure Time	Arrival Time	Origin	Destination	Aircraft
Monday	2:15:00	14:45:00	PVG	MXP	A330
Monday	6:45:00	13:25:00	AUH	MXP	B777
Monday	7:05:00	13:35:00	AUH	VCE	A330
Monday	09:30:00	20:10:00	FCO	ORD	A330
Monday	09:40:00	19:25:00	FCO	JFK	A330
Monday	10:10:00	23:15:00	FCO	LAX	B777
Monday	10:40:00	21:45:00	FCO	MIA	A330
Monday	5:40:00	18:10:00	NRT	MXP	B777
Monday	17:40:00	06:40:00	EZE	FCO	B777
Monday	13:00:00	22:10:00	MXP	JFK	A330
Monday	6:15:00	19:00:00	NRT	FCO	B777
Monday	6:30:00	19:05:00	ICN	FCO	A330
Monday	19:35:00	07:00:00	GIG	FCO	A330
Monday	21:50:00	07:20:00	ORD	FCO	A330
Monday	20:05:00	07:15:00	GRU	FCO	B777
Monday	15:15:00	01:10:00	FCO	YYZ	B777
Monday	15:20:00	3:30:00	FCO	NRT	B777
Monday	15:25:00	3:15:00	MXP	NRT	B777
Monday	01:15:00	13:10:00	LAX	FCO	B777
Monday	00:05:00	08:40:00	JFK	FCO	A330
Monday	02:30:00	10:40:00	JFK	MXP	A330
Monday	02:35:00	12:30:00	MIA	FCO	A330
Monday	21:45:00	11:40:00	FCO	EZE	B777
Monday	21:45:00	09:45:00	FCO	GIG	A330
Monday	21:55:00	3:55:00	VCE	AUH	A330
Monday	22:05:00	10:05:00	FCO	GRU	B777
Monday	22:10:00	4:15:00	MXP	AUH	B777
Monday	04:25:00	13:00:00	YYZ	FCO	B777

Table 1.2: Original Alitalia Schedule for Tuesday & Wednesday.

Day	Departure Time	Arrival Time	Origin	Destination	Aircraft
Tuesday	6:45:00	13:25:00	AUH	MXP	B777
Tuesday	7:05:00	13:35:00	AUH	VCE	A330
Tuesday	09:30:00	20:10:00	FCO	ORD	A330
Tuesday	09:40:00	19:25:00	FCO	JFK	A330
Tuesday	10:10:00	23:15:00	FCO	LAX	B777
Tuesday	10:40:00	21:45:00	FCO	MIA	A330
Tuesday	5:40:00	18:10:00	NRT	MXP	B777
Tuesday	17:40:00	06:40:00	EZE	FCO	B777
Tuesday	13:00:00	22:10:00	MXP	JFK	A330
Tuesday	6:15:00	19:00:00	NRT	FCO	B777
Tuesday	19:35:00	07:00:00	GIG	FCO	A330
Tuesday	21:50:00	07:20:00	ORD	FCO	A330
Tuesday	20:05:00	07:15:00	GRU	FCO	B777
Tuesday	15:15:00	01:10:00	FCO	YYZ	B777
Tuesday	15:20:00	3:30:00	FCO	NRT	B777
Tuesday	15:25:00	3:15:00	MXP	NRT	B777
Tuesday	01:15:00	13:10:00	LAX	FCO	B777
Tuesday	00:05:00	08:40:00	JFK	FCO	A330
Tuesday	02:30:00	10:40:00	JFK	MXP	A330
Tuesday	02:35:00	12:30:00	MIA	FCO	A330
Tuesday	21:45:00	09:45:00	FCO	GIG	A330
Tuesday	21:45:00	11:40:00	FCO	EZE	B777
Tuesday	21:55:00	3:55:00	VCE	AUH	A330
Tuesday	22:05:00	10:05:00	FCO	GRU	B777
Tuesday	22:10:00	4:15:00	MXP	AUH	B777
Tuesday	04:25:00	13:00:00	YYZ	FCO	B777
Wednesday	6:45:00	13:25:00	AUH	MXP	B777
Wednesday	7:05:00	13:35:00	AUH	VCE	A330
Wednesday	09:30:00	20:10:00	FCO	ORD	A330
Wednesday	09:40:00	19:25:00	FCO	JFK	A330
Wednesday	10:10:00	23:15:00	FCO	LAX	B777
Wednesday	10:40:00	21:45:00	FCO	MIA	A330
Wednesday	5:25:00	23:00:00	NRT	FCO	B777
Wednesday	17:40:00	06:40:00	EZE	FCO	B777
Wednesday	5:40:00	18:10:00	NRT	MXP	B777
Wednesday	12:55:00	0:15:00	MXP	PVG	A330
Wednesday	13:00:00	22:10:00	MXP	JFK	A330
Wednesday	6:15:00	19:00:00	NRT	FCO	B777
Wednesday	19:35:00	07:00:00	GIG	FCO	A330
Wednesday	21:50:00	07:20:00	ORD	FCO	A330
Wednesday	20:05:00	07:15:00	GRU	FCO	B777
Wednesday	15:15:00	01:10:00	FCO	YYZ	B777
Wednesday	15:20:00	3:30:00	FCO	NRT	B777
Wednesday	15:25:00	3:15:00	MXP	NRT	B777
Wednesday	01:15:00	13:10:00	LAX	FCO	B777
Wednesday	00:05:00	08:40:00	JFK	FCO	A330
Wednesday	02:30:00	10:40:00	JFK	MXP	A330
Wednesday	02:35:00	12:30:00	MIA	FCO	A330
Wednesday	21:45:00	11:40:00	FCO	EZE	B777
Wednesday	21:45:00	09:45:00	FCO	GIG	A330
Wednesday	21:55:00	3:55:00	VCE	AUH	A330
Wednesday	22:05:00	10:05:00	FCO	GRU	B777
Wednesday	22:10:00	4:15:00	MXP	AUH	B777
Wednesday	04:25:00	13:00:00	YYZ	FCO	B777

Table 1.3: Original Alitalia Schedule for Thursday & Friday.

Day	Departure Time	Arrival Time	Origin	Destination	Aircraft
Thursday	6:45:00	13:25:00	AUH	MXP	B777
Thursday	7:05:00	13:35:00	AUH	VCE	A330
Thursday	09:30:00	20:10:00	FCO	ORD	A330
Thursday	09:40:00	19:25:00	FCO	JFK	A330
Thursday	10:10:00	23:15:00	FCO	LAX	B777
Thursday	10:40:00	21:45:00	FCO	MIA	A330
Thursday	6:25:00	18:55:00	PVG	MXP	A330
Thursday	17:40:00	06:40:00	EZE	FCO	B777
Thursday	5:40:00	18:10:00	NRT	MXP	B777
Thursday	13:00:00	22:10:00	MXP	JFK	A330
Thursday	6:15:00	19:00:00	NRT	FCO	B777
Thursday	19:35:00	07:00:00	GIG	FCO	A330
Thursday	21:50:00	07:20:00	ORD	FCO	A330
Thursday	15:00:00	2:25:00	FCO	ICN	A330
Thursday	20:05:00	07:15:00	GRU	FCO	B777
Thursday	15:15:00	01:10:00	FCO	YYZ	B777
Thursday	15:20:00	3:30:00	FCO	NRT	B777
Thursday	15:25:00	3:15:00	MXP	NRT	B777
Thursday	01:15:00	13:10:00	LAX	FCO	B777
Thursday	00:05:00	08:40:00	JFK	FCO	A330
Thursday	02:30:00	10:40:00	JFK	MXP	A330
Thursday	02:35:00	12:30:00	MIA	FCO	A330
Thursday	21:45:00	11:40:00	FCO	EZE	B777
Thursday	21:45:00	09:45:00	FCO	GIG	A330
Thursday	21:55:00	3:55:00	VCE	AUH	A330
Thursday	22:05:00	10:05:00	FCO	GRU	B777
Thursday	22:10:00	4:15:00	MXP	AUH	B777
Thursday	04:25:00	13:00:00	YYZ	FCO	B777
Friday	6:45:00	13:25:00	AUH	MXP	B777
Friday	7:05:00	13:35:00	AUH	VCE	A330
Friday	09:30:00	20:10:00	FCO	ORD	A330
Friday	09:40:00	19:25:00	FCO	JFK	A330
Friday	10:10:00	23:15:00	FCO	LAX	B777
Friday	10:40:00	21:45:00	FCO	MIA	A330
Friday	5:25:00	23:00:00	NRT	FCO	B777
Friday	5:40:00	18:10:00	NRT	MXP	B777
Friday	17:40:00	06:40:00	EZE	FCO	B777
Friday	12:55:00	0:15:00	MXP	PVG	A330
Friday	13:00:00	22:10:00	MXP	JFK	A330
Friday	6:15:00	19:00:00	NRT	FCO	B777
Friday	6:30:00	19:05:00	ICN	FCO	A330
Friday	19:35:00	07:00:00	GIG	FCO	A330
Friday	21:50:00	07:20:00	ORD	FCO	A330
Friday	20:05:00	07:15:00	GRU	FCO	B777
Friday	15:15:00	01:10:00	FCO	YYZ	B777
Friday	15:20:00	3:30:00	FCO	NRT	B777
Friday	15:25:00	3:15:00	MXP	NRT	B777
Friday	01:15:00	13:10:00	LAX	FCO	B777
Friday	00:05:00	08:40:00	JFK	FCO	A330
Friday	02:30:00	10:40:00	JFK	MXP	A330
Friday	02:35:00	12:30:00	MIA	FCO	A330
Friday	21:45:00	09:45:00	FCO	GIG	A330
Friday	21:45:00	11:40:00	FCO	EZE	B777
Friday	21:55:00	3:55:00	VCE	AUH	A330
Friday	22:05:00	10:05:00	FCO	GRU	B777
Friday	22:10:00	4:15:00	MXP	AUH	B777
Friday	04:25:00	13:00:00	YYZ	FCO	B777

Table 1.4: Original Alitalia Schedule for Saturday & Sunday.

Day	Departure Time	Arrival Time	Origin	Destination	Aircraft
Saturday	6:45:00	13:25:00	AUH	MXP	B777
Saturday	7:05:00	13:35:00	AUH	VCE	A330
Saturday	09:30:00	20:10:00	FCO	ORD	A330
Saturday	09:40:00	19:25:00	FCO	JFK	A330
Saturday	10:10:00	23:15:00	FCO	LAX	B777
Saturday	10:40:00	21:45:00	FCO	MIA	A330
Saturday	6:35:00	19:05:00	PVG	MXP	A330
Saturday	5:40:00	18:10:00	NRT	MXP	B777
Saturday	17:40:00	06:40:00	EZE	FCO	B777
Saturday	13:00:00	22:10:00	MXP	JFK	A330
Saturday	6:15:00	19:00:00	NRT	FCO	B777
Saturday	19:35:00	07:00:00	GIG	FCO	A330
Saturday	21:50:00	07:20:00	ORD	FCO	A330
Saturday	15:00:00	2:25:00	FCO	ICN	A330
Saturday	20:05:00	07:15:00	GRU	FCO	B777
Saturday	15:15:00	01:10:00	FCO	YYZ	B777
Saturday	15:20:00	3:30:00	FCO	NRT	B777
Saturday	15:25:00	3:15:00	MXP	NRT	B777
Saturday	01:15:00	13:10:00	LAX	FCO	B777
Saturday	00:05:00	08:40:00	JFK	FCO	A330
Saturday	02:30:00	10:40:00	JFK	MXP	A330
Saturday	02:35:00	12:30:00	MIA	FCO	A330
Saturday	21:45:00	11:40:00	FCO	EZE	B777
Saturday	21:45:00	09:45:00	FCO	GIG	A330
Saturday	21:55:00	3:55:00	VCE	AUH	A330
Saturday	22:05:00	10:05:00	FCO	GRU	B777
Saturday	22:10:00	4:15:00	MXP	AUH	B777
Saturday	04:25:00	13:00:00	YYZ	FCO	B777
Sunday	6:45:00	13:25:00	AUH	MXP	B777
Sunday	7:05:00	13:35:00	AUH	VCE	A330
Sunday	09:30:00	20:10:00	FCO	ORD	A330
Sunday	09:40:00	19:25:00	FCO	JFK	A330
Sunday	10:10:00	23:15:00	FCO	LAX	B777
Sunday	10:40:00	21:45:00	FCO	MIA	A330
Sunday	17:40:00	06:40:00	EZE	FCO	B777
Sunday	5:40:00	18:10:00	NRT	MXP	B777
Sunday	12:55:00	0:15:00	MXP	PVG	A330
Sunday	13:00:00	22:10:00	MXP	JFK	A330
Sunday	6:15:00	19:00:00	NRT	FCO	B777
Sunday	6:30:00	19:05:00	ICN	FCO	A330
Sunday	19:35:00	07:00:00	GIG	FCO	A330
Sunday	21:50:00	07:20:00	ORD	FCO	A330
Sunday	15:00:00	2:25:00	FCO	ICN	A330
Sunday	20:05:00	07:15:00	GRU	FCO	B777
Sunday	15:15:00	01:10:00	FCO	YYZ	B777
Sunday	15:20:00	3:30:00	FCO	NRT	B777
Sunday	15:25:00	3:15:00	MXP	NRT	B777
Sunday	01:15:00	13:10:00	LAX	FCO	B777
Sunday	00:05:00	08:40:00	JFK	FCO	A330
Sunday	02:30:00	10:40:00	JFK	MXP	A330
Sunday	02:35:00	12:30:00	MIA	FCO	A330
Sunday	21:45:00	09:45:00	FCO	GIG	A330
Sunday	21:45:00	11:40:00	FCO	EZE	B777
Sunday	21:55:00	3:55:00	VCE	AUH	A330
Sunday	22:05:00	10:05:00	FCO	GRU	B777
Sunday	22:10:00	4:15:00	MXP	AUH	B777
Sunday	04:25:00	13:00:00	YYZ	FCO	B777

2

Schedule of the Standard Case

The following schedule results from de modelling of the standard case (no ISO).

Table 2.1: Schedule for the Standard Case

Day	Departure Time	Arrival Time	Origin	Destination	Aircraft
Monday	9:40:00	12:40:00	FCO	JFK	A330
Monday	10:40:00	13:00:00	MXP	JFK	A330
Monday	13:40:00	16:20:00	FCO	MIA	B777
Monday	14:40:00	05:00:00	JFK	MXP	A330
Monday	15:40:00	06:40:00	JFK	FCO	A330
Monday	17:50:00	20:10:00	MXP	JFK	A330
Monday	18:40:00	9:20:00	MIA	FCO	B777
Monday	22:50:00	07:10:00	MXP	AUH	A330
Monday	22:50:00	05:10:00	FCO	EZE	B777
Monday	22:50:00	03:30:00	FCO	GRU	B777
Monday	22:50:00	13:10:00	JFK	MXP	A330
Tuesday	06:40:00	09:40:00	FCO	JFK	A330
Tuesday	07:40:00	10:20:00	FCO	MIA	B777
Tuesday	08:10:00	10:30:00	MXP	JFK	A330
Tuesday	09:40:00	02:00:00	EZE	FCO	B777
Tuesday	09:50:00	14:10:00	AUH	MXP	A330
Tuesday	11:50:00	20:10:00	MXP	AUH	A330
Tuesday	12:10:00	02:50:00	GRU	FCO	B777
Tuesday	13:10:00	03:30:00	JFK	MXP	A330
Tuesday	15:10:00	06:10:00	JFK	FCO	A330
Tuesday	15:50:00	18:10:00	MXP	JFK	A330
Tuesday	16:50:00	01:10:00	MXP	AUH	A330
Tuesday	17:40:00	08:20:00	MIA	FCO	B777
Tuesday	18:50:00	01:10:00	FCO	EZE	B777
Tuesday	19:10:00	23:50:00	FCO	GRU	B777

Table 2.2: Schedule for the Standard Case

Day	Departure Time	Arrival Time	Origin	Destination	Aircraft
Wednesday	05:10:00	11:10:00	JFK	MXP	A330
Wednesday	05:50:00	10:10:00	AUH	MXP	A330
Wednesday	07:40:00	10:20:00	FCO	MIA	B777
Wednesday	08:10:00	10:30:00	MXP	JFK	A330
Wednesday	08:10:00	11:10:00	FCO	JFK	A330
Wednesday	09:40:00	2:00:00	EZE	FCO	B777
Wednesday	10:00:00	05:20:00	MXP	PVG	B777
Wednesday	11:50:00	16:10:00	AUH	MXP	A330
Wednesday	12:10:00	2:50:00	GRU	FCO	B777
Wednesday	12:50:00	21:10:00	MXP	AUH	A330
Wednesday	13:00:00	15:40:00	FCO	MIA	B777
Wednesday	13:10:00	3:30:00	JFK	MXP	A330
Wednesday	13:50:00	16:10:00	MXP	JFK	A330
Wednesday	15:10:00	6:10:00	JFK	FCO	A330
Wednesday	17:40:00	8:20:00	MIA	FCO	B777
Wednesday	18:50:00	01:10:00	FCO	EZE	B777
Wednesday	18:50:00	9:10:00	JFK	MXP	A330
Wednesday	19:10:00	02:10:00	FCO	GRU	A330
Wednesday	22:10:00	06:30:00	MXP	AUH	A330
Thursday	05:50:00	10:10:00	AUH	MXP	A330
Thursday	08:10:00	10:30:00	MXP	JFK	A330
Thursday	08:10:00	11:10:00	FCO	JFK	A330
Thursday	10:50:00	12:00:00	FCO	JFK	B777
Thursday	11:10:00	15:30:00	AUH	MXP	A330
Thursday	11:50:00	14:10:00	MXP	JFK	A330
Thursday	12:00:00	08:10:00	FCO	ICN	B777
Thursday	12:10:00	05:10:00	GRU	FCO	A330
Thursday	12:50:00	21:10:00	MXP	AUH	A330
Thursday	13:30:00	12:50:00	PVG	MXP	B777
Thursday	14:40:00	2:00:00	EZE	FCO	B777
Thursday	15:10:00	6:10:00	JFK	FCO	A330
Thursday	16:50:00	7:10:00	JFK	MXP	A330
Thursday	17:40:00	8:20:00	MIA	FCO	B777
Thursday	18:50:00	01:10:00	FCO	EZE	B777
Thursday	22:10:00	06:30:00	MXP	AUH	A330
Thursday	22:20:00	12:40:00	JFK	MXP	A330
Friday	05:50:00	10:10:00	AUH	MXP	A330
Friday	06:40:00	19:50:00	JFK	FCO	B777
Friday	07:40:00	10:20:00	FCO	MIA	B777
Friday	09:40:00	2:00:00	EZE	FCO	B777
Friday	09:50:00	12:10:00	MXP	JFK	A330
Friday	10:00:00	05:20:00	MXP	PVG	B777
Friday	11:10:00	15:30:00	AUH	MXP	A330
Friday	12:50:00	21:10:00	MXP	AUH	A330
Friday	12:50:00	15:50:00	FCO	JFK	A330
Friday	14:30:00	12:40:00	ICN	FCO	B777
Friday	14:50:00	5:10:00	JFK	MXP	A330
Friday	15:20:00	17:40:00	MXP	JFK	A330
Friday	17:40:00	8:20:00	MIA	FCO	B777
Friday	17:50:00	8:50:00	JFK	FCO	A330
Friday	18:50:00	01:10:00	FCO	EZE	B777
Friday	19:10:00	23:50:00	FCO	GRU	B777
Friday	20:20:00	10:40:00	JFK	MXP	A330
Friday	22:10:00	06:30:00	MXP	AUH	A330

Table 2.3: Schedule for the Standard Case

Day	Departure Time	Arrival Time	Origin	Destination	Aircraft
Saturday	05:50:00	10:10:00	AUH	MXP	A330
Saturday	06:40:00	09:40:00	FCO	JFK	A330
Saturday	08:10:00	10:30:00	MXP	JFK	A330
Saturday	09:40:00	02:00:00	EZE	FCO	B777
Saturday	10:40:00	13:20:00	FCO	MIA	B777
Saturday	11:50:00	16:10:00	AUH	MXP	A330
Saturday	12:00:00	10:30:00	FCO	ICN	A330
Saturday	12:10:00	02:50:00	GRU	FCO	B777
Saturday	12:50:00	21:10:00	MXP	AUH	A330
Saturday	13:40:00	13:00:00	PVG	MXP	B777
Saturday	14:00:00	16:20:00	MXP	JFK	A330
Saturday	15:00:00	05:20:00	JFK	MXP	A330
Saturday	17:40:00	08:20:00	MIA	FCO	B777
Saturday	18:50:00	01:10:00	FCO	EZE	B777
Saturday	19:00:00	10:00:00	JFK	FCO	A330
Saturday	19:10:00	23:50:00	FCO	GRU	B777
Saturday	21:40:00	06:00:00	MXP	AUH	A330
Sunday	05:00:00	20:00:00	JFK	FCO	A330
Sunday	05:50:00	10:10:00	AUH	MXP	A330
Sunday	06:40:00	07:50:00	FCO	JFK	B777
Sunday	07:40:00	10:20:00	FCO	MIA	B777
Sunday	08:10:00	10:30:00	MXP	JFK	A330
Sunday	09:40:00	2:00:00	EZE	FCO	B777
Sunday	11:00:00	15:20:00	AUH	MXP	A330
Sunday	12:00:00	15:00:00	FCO	JFK	A330
Sunday	12:10:00	2:50:00	GRU	FCO	B777
Sunday	12:50:00	15:10:00	MXP	JFK	A330
Sunday	13:10:00	3:30:00	JFK	MXP	A330
Sunday	14:40:00	15:10:00	ICN	FCO	A330
Sunday	15:10:00	4:20:00	JFK	FCO	B777
Sunday	17:00:00	8:00:00	JFK	FCO	A330
Sunday	17:40:00	8:20:00	MIA	FCO	B777
Sunday	17:50:00	8:10:00	JFK	MXP	A330

3

Synthetic Demand Generation

As it was mentioned in the paper, the demand is generated based on the schedule for Alitalia presented in chapter 1. Note that the table contains local times for departure and arrival. Since the demand needs to be computed in model times, the first steps is to compute the necessary time changes to have every input in the required time zone. To estimate the demand served by each flight the average passenger capacity is considered for each aircraft. This is to account for the fact that there are multiple potential configurations per vehicle. Once the Alitalia demand is known per time step, it is necessary to add the extra demand arising from flights operated by different airlines for the same routes. These flights are repeated, following the same schedule, every day of the week.

Table 3.1: Schedule for other airlines that fly the same long-haul routes as Alitalia.

Day	**Departure_time**	**Origin**	**Destination**	**Operated**	**Aircraft**
All	08:55:00	AUH	MXP	Etihad	A330
All	09:40:00	JFK	FCO	American Airlines	B777
All	10:00:00	FCO	JFK	American Airlines	B777
All	11:10:00	MXP	JFK	American Airlines	B777
All	12:50:00	FCO	YYZ	Air Canada	A330
All	14:50:00	MXP	AUH	Etihad	A330
All	16:10:00	MXP	JFK	Emirates	B777
All	18:35:00	YYZ	FCO	Air Canada	A330
All	19:20:00	JFK	MXP	American Airlines	B777
All	22:20:00	JFK	MXP	Emirates	B777

From the point demand known at every time step, it is left to spread it over the attraction band. The attraction band is the time-period over which we assume passengers can be captured. This means, for instance, that the passengers that belong to the demand generated by the 10 am flights would also be available to travel three hours before and three hours after set time. Adding the total number of passengers within the attraction band results in the flight demand for each time step. The synthetic demand for each route considered in the model can be observed in the figures below. Note that the peak times math the departure times of the flights in the input schedule.

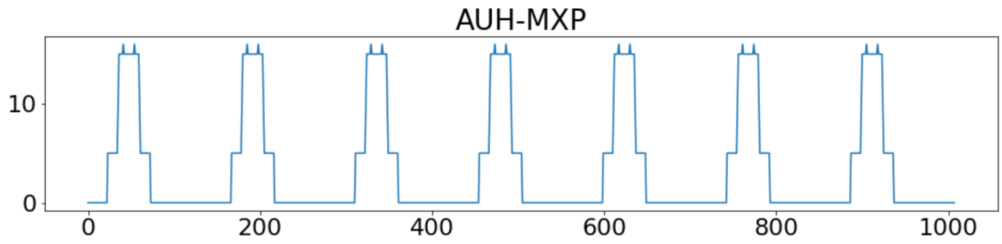

Figure 3.1: Demand for the route AUH-MXP.

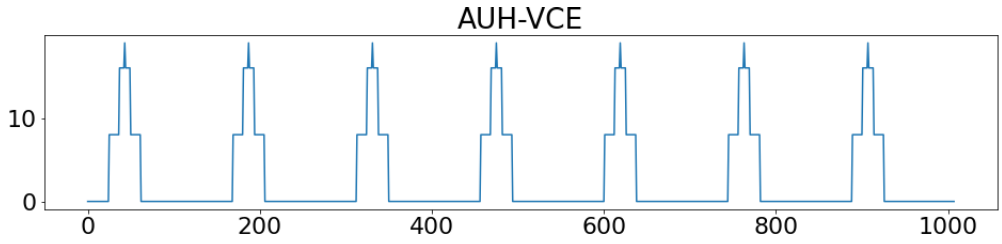

Figure 3.2: Demand for the route AUH-VCE.

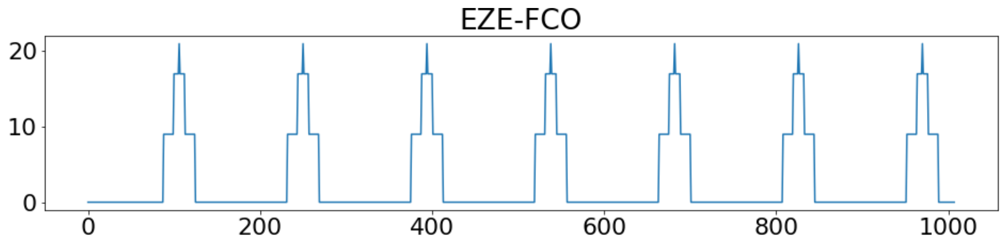

Figure 3.3: Demand for the route EZE-FCO.

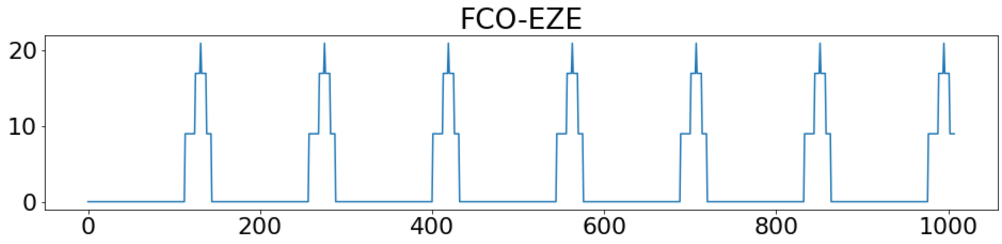

Figure 3.4: Demand for the route FCO-EZE.

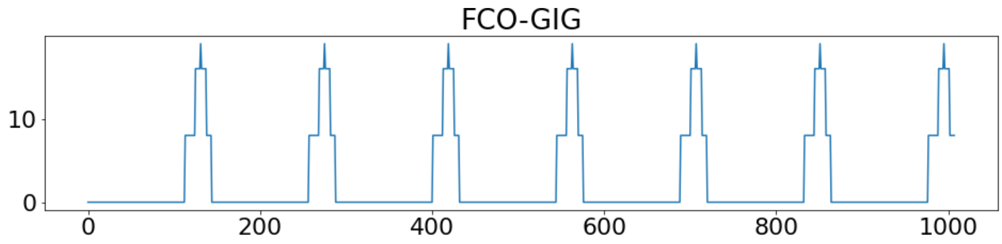

Figure 3.5: Demand for the route FCO-GIG.

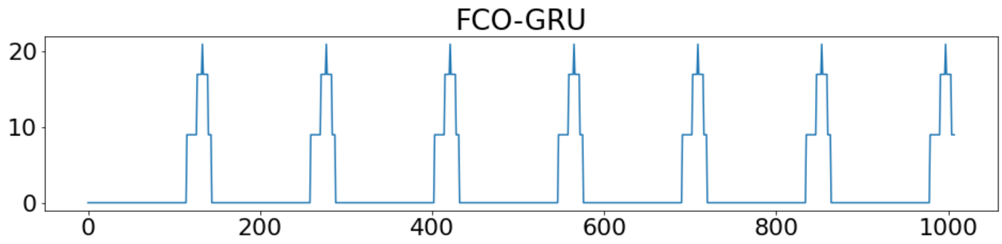

Figure 3.6: Demand for the route FCO-GRU.

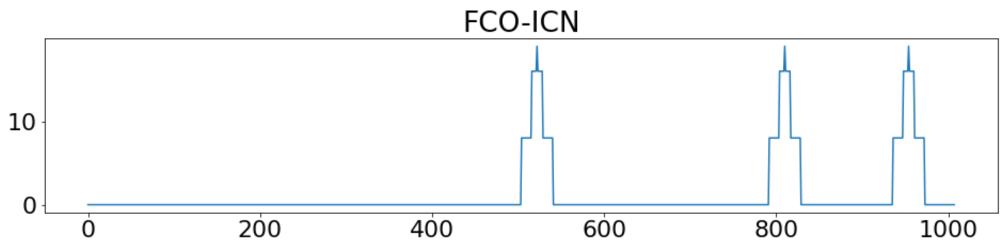

Figure 3.7: Demand for the route FCO-ICN.

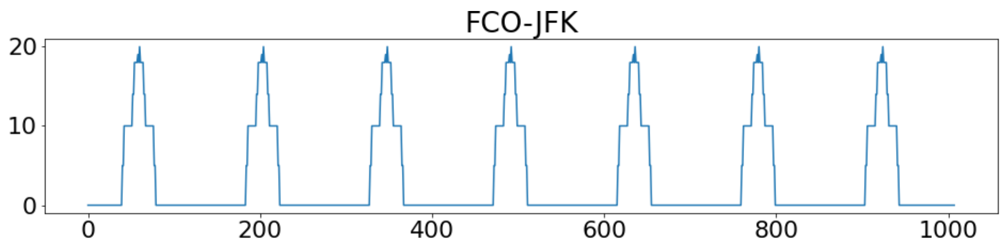

Figure 3.8: Demand for the route FCO-JFK.

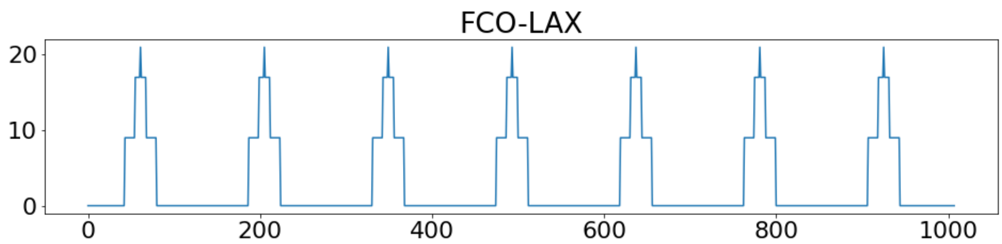

Figure 3.9: Demand for the route FCO-LAX.

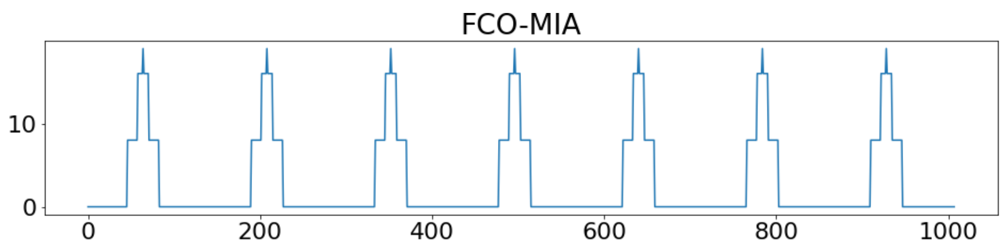

Figure 3.10: Demand for the route FCO-MIA.

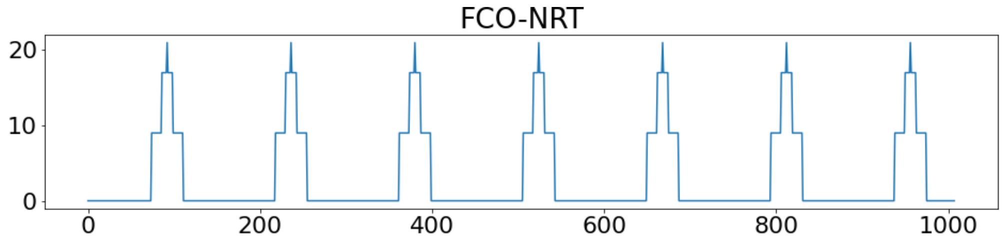

Figure 3.11: Demand for the route FCO-NRT.

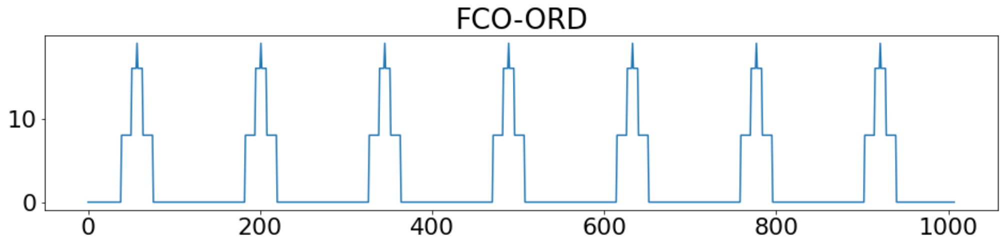

Figure 3.12: Demand for the route FCO-ORD.

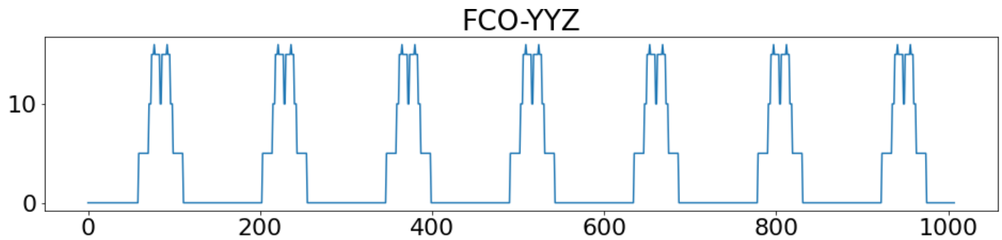

Figure 3.13: Demand for the route FCO-YYZ.

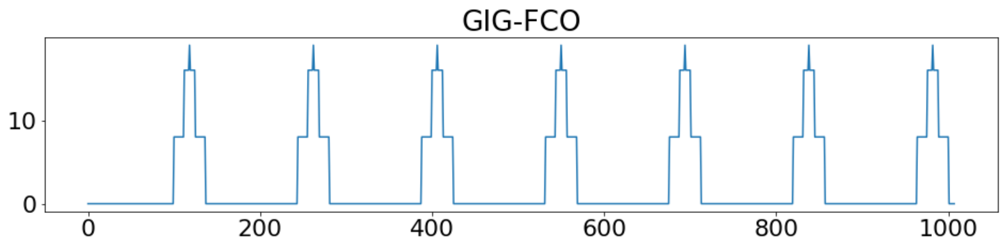

Figure 3.14: Demand for the route GIG-FCO.

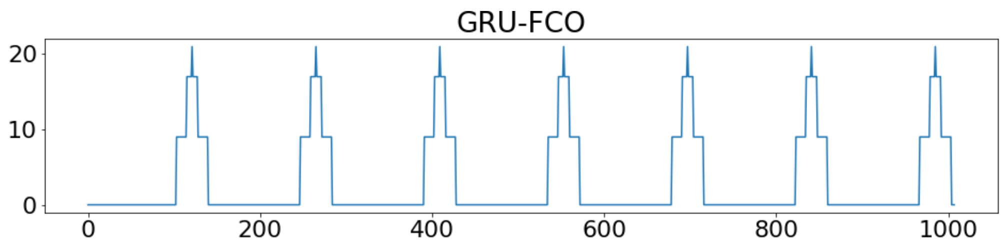

Figure 3.15: Demand for the route GRU-FCO.

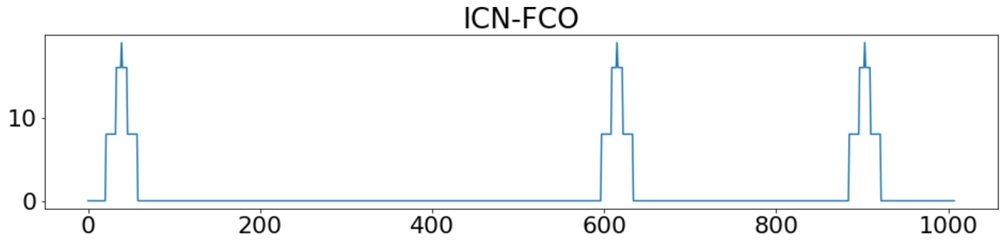

Figure 3.16: Demand for the route ICN-FCO.

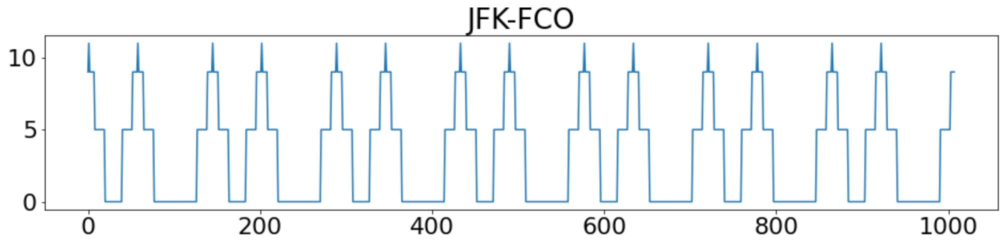

Figure 3.17: Demand for the route JFK-FCO.

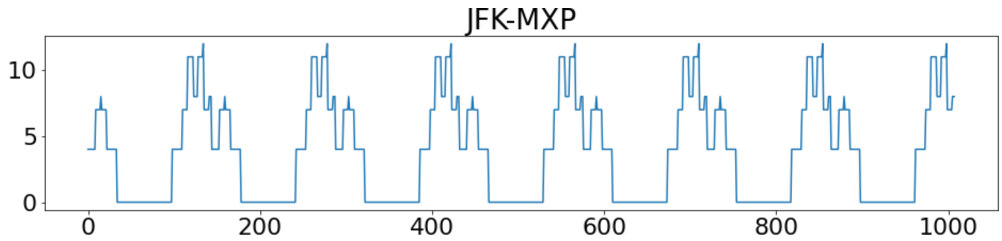

Figure 3.18: Demand for the route JFK-MXP.

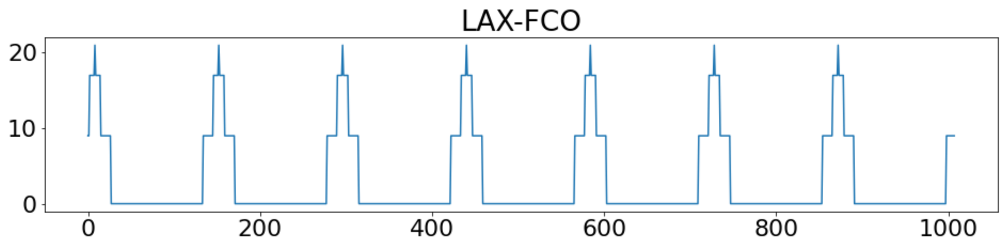

Figure 3.19: Demand for the route LAX-FCO.

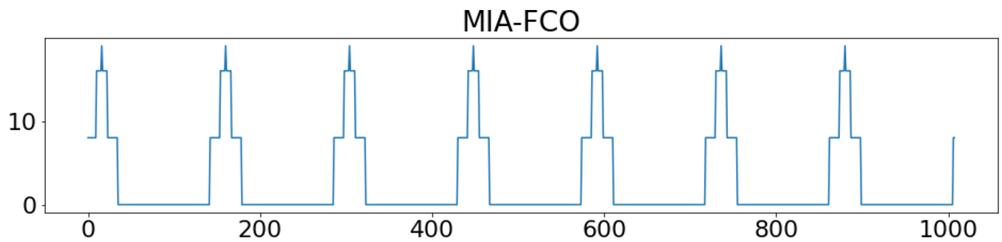

Figure 3.20: Demand for the route MIA-FCO.

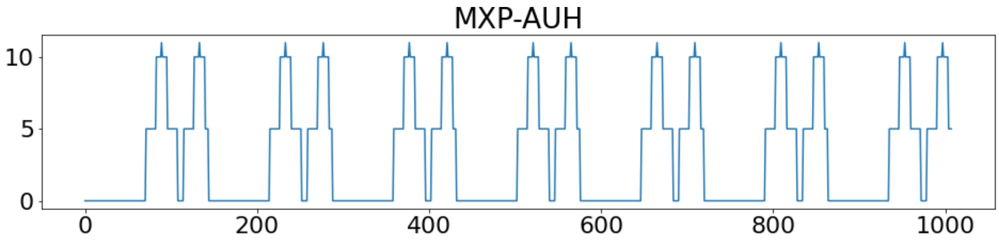

Figure 3.21: Demand for the route MXP-AUH.

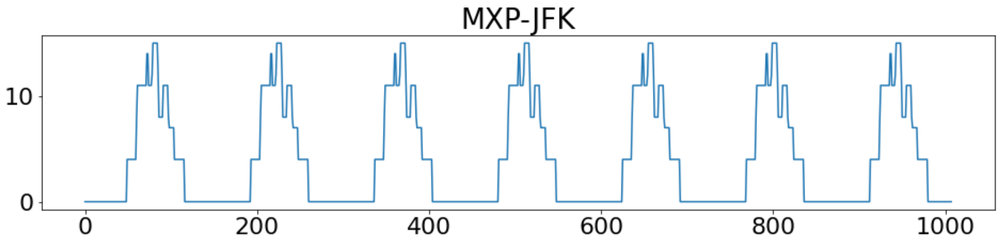

Figure 3.22: Demand for the route MXP-JFK.

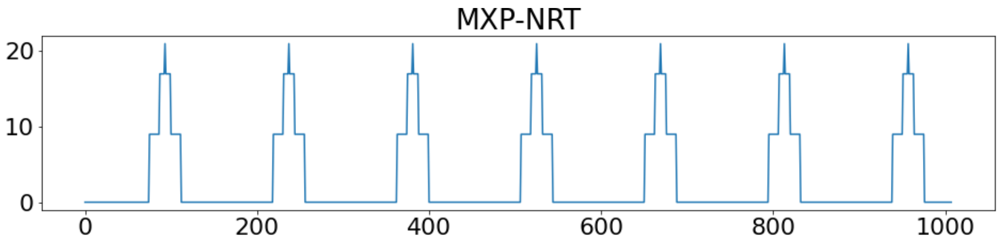

Figure 3.23: Demand for the route MXP-NRT.

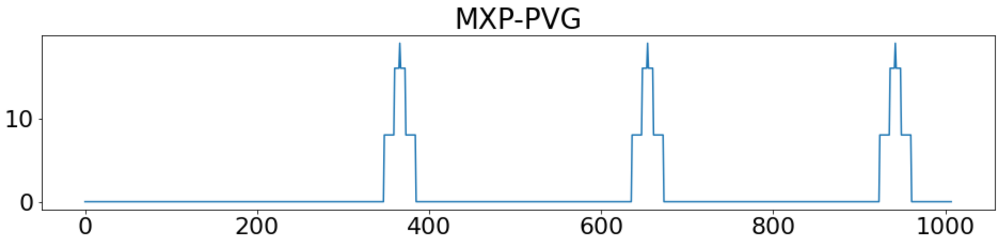

Figure 3.24: Demand for the route MXP-PVG.

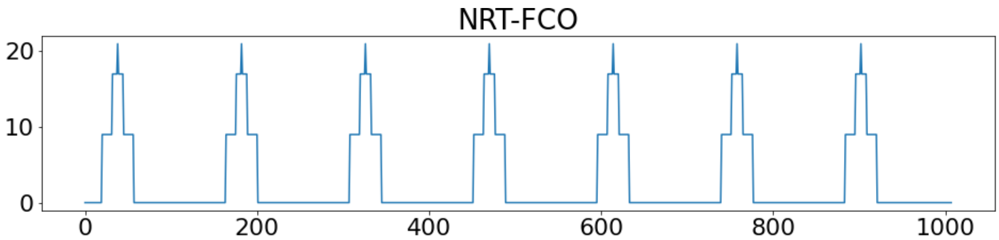

Figure 3.25: Demand for the route NRT-FCO.

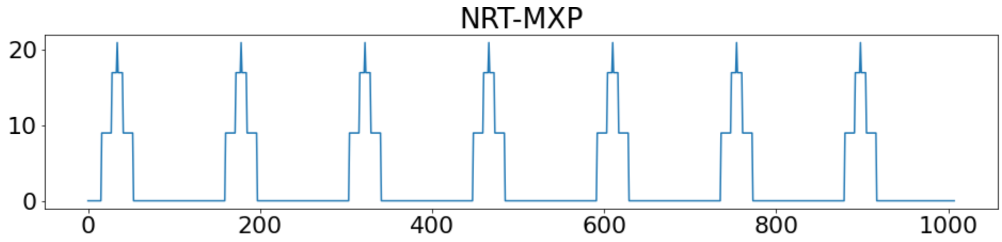

Figure 3.26: Demand for the route NRT-MXP.

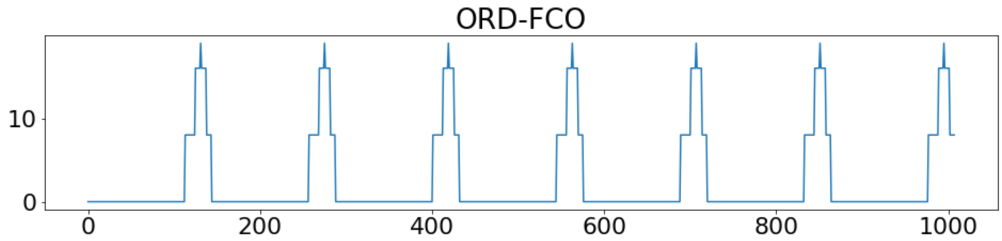

Figure 3.27: Demand for the route ORD-FCO.

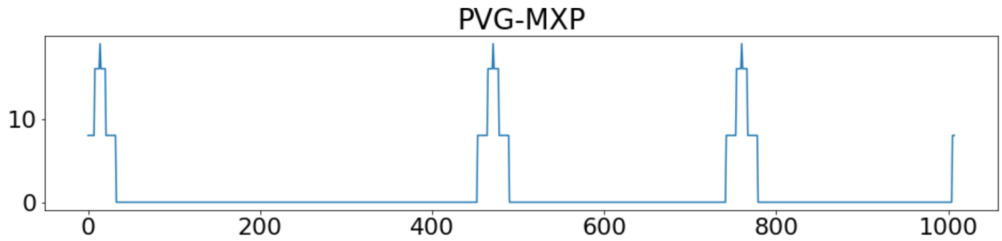

Figure 3.28: Demand for the route PVG-MXP.

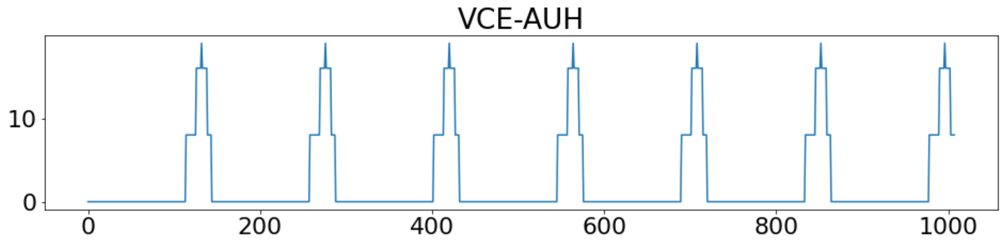

Figure 3.29: Demand for the route VCE-AUH.

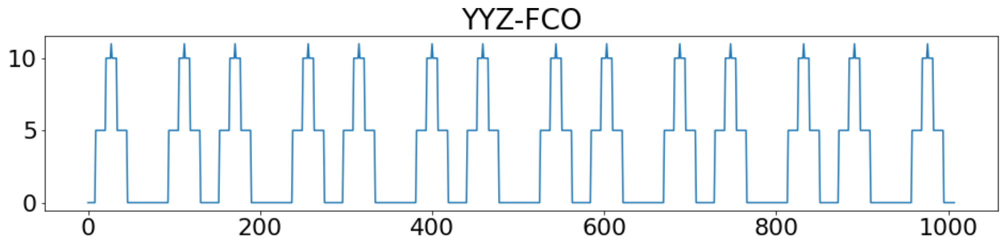

Figure 3.30: Demand for the route YYZ-FCO.

4

ISO Locations

This chapter provides an analysis of the locations of the stop-over airports. For each route, the direct flight distance is presented, as well as the two legs distances. The deviation expresses the percentage on which the total two-leg distance increases with respect to the direct one.

- **Milan - Abu Dhabi** (MXP-AUH) : 4,717.588 km
  Stop airport: LCA (Larnaca, Cypruss)
  - MXP - LCA : 2,416.718 km
  - LCA - AUH : 2,334.659 km

  Deviation : + 0.7%

- **Venice - Abu Dhabi** (VCE-AUH) : 4,442.449 km
  Stop airport: LCA (Larnaca, Cypruss)
  - VCE - LCA : 2,151.233 km
  - LCA - AUH : 2,334.659 km

  Deviation : + 1.0%

- **Rome - Buenos Aires** (FCO-EZE) : 11,132.671 km
  Stop airport: SID (Sal, Cabo Verde)
  - FCO - SID : 4,353.954km
  - SID - EZE : 6,833.423km

  Deviation : + 0.5%

- **Rome - Chicago** (FCO-ORD) : 7,760.207 km
  Stop airport: YYR (Goose Bay, Canada)
  - FCO - YYR : 5,367.624 km
  - YYR - ORD : 2,395.801 km

  Deviation : + 0.0%

- **Rome - Los Angeles** (FCO-LAX) : 10,223.586 km
  Stop airport: YFB (Iqaluit, Canada)
  - FCO - YFB : 5,509.216 km
  - YFB - LAX : 4,732.069 km

  Deviation : + 0.2%

- **Milan - New York** (MXP-JFK) : 6,427.955 km
  Stop airport: YYT (St. John's, Canada)
  - MXP - YYT : 4,587.259 km
  - YYT - JFK : 1,843. 914 km

  Deviation : + 0.0%
- **Milan - Shanghai** (MXP-PVG) : 9,161.646 km
  Stop airport: OMS (Omsk, Russia)
  - MXP - OMS : 4,542.207 km
  - OMS - PVG : 4,617.830 km

  Deviation : + 0.0%
- **Milan - Tokyo** (MXP-NRT) : 9,769.848 km
  Stop airport: KJA (Krasnoyarsk, Russia)
  - MXP - KJA : 5,629.891 km
  - KJA - NRT : 4,228.452 km

  Deviation : + 0.9 %
- **Rome - New York** (FCO-JFK) : 6,881.693 km
  Stop airport: YYT (St. John's, Canada)
  - FCO - YYT : 5,037.779 km
  - YYT - JFK : 1,843.914 km

  Deviation : + 0.0%
- **Rome - Rio de Janeiro** (FCO-GIG) : 9,150.383 km
  Stop airport: DSS (Dakar, Senegal)
  - FCO - DSS : 4,120.649 km
  - DSS - GIG : 5,031.343 km

  Deviation : + 0.0 %
- **Rome - Miami** (FCO-MIA) : 8,344.274 km
  Stop airport: TER (Azores, Portugal)
  - FCO - TER : 3,332.239 km
  - TER - MIA : 5,137.537 km

  Deviation : + 1.5%
- **Rome - Sao Paulo** (FCO-GRU) : 9,412.65 km
  Stop airport: DSS (Dakar, Senegal)
  - FCO - DSS : 4,120.649 km
  - DSS - GRU : 5,292.001 km

  Deviation : + 0.0 %
- **Rome - Seoul** (FCO-ICN) : 8,984.656 km
  Stop airport: OMS (Omsk, Russia)
  - FCO - OMS : 4,587.259 km

  - OMS - ICN : 4,403.833 km

  Deviation : + 0.1%

- **Rome - Tokyo** (FCO-NRT) : 9,925.921 km
  Stop airport: KJA (Krasnoyarsk, Russia)

  - FCO - KJA : 5,728.040 km
  - KJA - NRT : 4,228.452 km

  Deviation : + 0.3%

- **Rome - Toronto** (FCO-YYZ) : 7,103.735 km
  Stop airport: YYT (St. John's, Canada)

  - FCO - YYT : 5,037.779 km
  - YYT - YYZ : 2,128.707

  Deviation : + 0.9%