# Study to the adaptation of electrified aircraft by regional airlines

using strategic airline planning and aircraft design

Noa Zuijderwijk

June, 2022


TUDelft

Cover image by MAHEPA [2]

# Study to the adaptation of electrified aircraft by regional airlines

using strategic airline planning and aircraft design

by

Noa Zuijderwijk

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on June 2nd, 2022.

| | | |
|---|---|---|
| Student number: | 4462343 | |
| Project duration: | June, 2021 - June, 2022 | |
| Thesis committee: | Dr. B.F. Lopes Dos Santos | TU Delft, Chair |
| | Dr. M.F.M. Hoogreef | TU Delft, Supervisor |
| | Dr. P.J. Proesmans | TU Delft, Examiner |
| | Dr. P.C. Roling | TU Delft, Examiner |

# Acknowledgements

For the past year, I dedicated myself to the last part of my study program, this research project. Over my study period, I enjoyed working individually while I was surrounded by fellow students. But to work on such a free individual project for quite a long time was challenging. Especially when the university is closed and you are distant from fellow students. The routine of always having a project group, a discussion, and a fixed assignment transferred to a yet-to-be-defined project where all the decisions are up to you. I noticed how much I value the thoughts and enthusiasm of others. Nevertheless, I learned a lot about assessing problems myself, trusting in your own decisions, and feeling confident about the steps you take. Moreover, I would like to give special attention to the following people:

Starting with my supervisors, Bruno and Maurice. Throughout the last year, your enthusiasm for the project was high, and together with your feedback, you encouraged me to challenge myself and to define and improve the project. Thank you for your ideas and time. I also want to thank Pieter-Jan, for the insights during our conversations and on the paper. Thereby, I want to thank the team of SATA Air Açores, for their time, insights, and data provision.

Then my family, for the love and support whenever I needed it, but especially for all the enjoyable moments together. You were always available for a call, a stroll, or an activity, which I appreciate more than I can say in words.

And last but not least, my friends, in special my roommates and boyfriend, for listening to all my ideas and grumpy moments. Thank you for being my study partners on the working from home days, with good coffee, lunch breaks, short (or longer ;) ) walks, and occasionally a beer at the end of the day. It would have been a lot less fun without you.

Thank you all,

Noa

Delft, June 2022

# Contents

# List of Figures



## I Scientific Paper



## II Literature Study



## III Research Methodologies

# List of Tables



## I Scientific Paper



## II Literature Study



## III Research Methodologies

# List of Abbreviations and Symbols

| | |
|---|---|
| $\eta$ | Conversion or transmission efficiencies |
| $\phi$ | Supplied power ratio of the battery |
| $e_b$ | Specific battery energy |
| $e_f$ | Specific fuel energy |
| $E_{0\_tot}$ | Total energy at the start |
| $g$ | Gravitational acceleration |
| $L/D$ | Lift over drag ratio |
| $W_b$ | Battery weight |
| $W_f$ | Fuel weight |
| $W_{OE}$ | Operating empty weight without batteries |
| $W_{PL}$ | Payload weight |
| BRS | Battery Recharging Station |
| BSS | Battery Swapping Station |
| BT | Maximum block time |
| CHYLA | Credible HYbrid eLectric Aircraft |
| $CO_2$ | Carbon dioxide |
| FAA | Federal Aviation Administration |
| FE | Fully-electric |
| HE | Hybrid-electric |
| IATA | International Air Transport Association |
| ICAO | International Civil Aviation Organization |
| KE | Kerosene |
| LF | Load factor |
| LP | Linear Programming |
| LTOt | Landing and take-off time |
| MINLP | Mixed Integer Non-Linear Programming |
| MTOM | Maximum Take-Off Mass |
| MTOW | Maximum Take-Off Weight |
| OF | Objective Function |
| period | Time span in days |

| | |
|---|---|
| PSO | Public Service Obligation |
| PSOcap | PSO capacity |
| PSOfreq | PSO frequency |
| R | Aircraft range |
| RT | Reloading time, difference in turnaround time with and without refueling and/or recharging |
| SF | Stop factor for yield |
| TAT | Turnaround time |
| TF | Transfer factor for yield |

# Introduction

The environmental impact of the aviation sector needs to be reduced. Therefore, climate goals have been set in Europe as stated in the Paris Agreement [3] and the European Green Deal [1]. The Destination 2050 report [4] presents different measures to achieve this goal. One of these measures is to focus on aircraft and engine technologies and replace current kerosene aircraft with electrified aircraft. Electrified aircraft are driven (partly) by electrical battery energy which results in less $CO_2$ emission and thus a reduction in environmental impact. At the TU Delft as part of the Clean Sky2 program, the CHYLA-project is established to identify Credible HYbrid eLectric Aircraft (CHYLA) [5]. This project evaluates if hybrid-electric aircraft can potentially serve and replace larger transport aircraft.

To realize a fleet replacement by electrified aircraft, the transition to these aircraft should be attractive for airlines. For airlines, profit is an important performance indicator for making strategic decisions such as fleet replacement. Therefore, operating electrified aircraft should be profitable for the airline in order to make a transition. Of course, measures such as a climate tax or subsidies can stimulate the choice for electrified aircraft as well.

The fleet replacement of airlines is generally planned with fleet planning models, which are strategic models. In these models, a set of aircraft is given and the most profitable combination is selected. The profitability of electrified aircraft can be studied this way. However, electrified aircraft for larger transport purposes are yet in a conceptual design phase, see the CHYLA project. This brings opportunities since the aircraft design is not fixed and can be shaped by the airlines' desires. The combination of strategic airline planning, the operation of electrified aircraft, and the design of electrified aircraft arises, as visualized in Figure 1. In earlier research, strategic airline planning and aircraft design have been combined, but the operation and design of electrified aircraft are not considered.

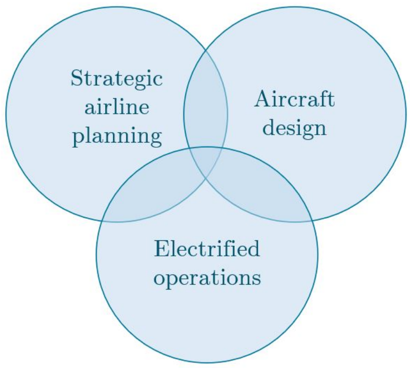



Figure 1: Visualization of research elements

A connection between strategic airline planning and electrified aircraft design is presented in this thesis. Both the adaptation of an airline on electrified aircraft and the selected aircraft designs can be studied. The project is shared with various regional European airlines, and the airline SATA Air Açores is implemented as a case study. Besides the cooperation with SATA Air Açores, the CHYLA members received updates on the project development as well.

This thesis presents the Scientific Paper in Part I, the Literature Study in Part II and the Research Methodologies in Part III. Supplementary work presents sensitivity analyses in Part IV.

# I

## Scientific Paper

# Study to the adaptation of electrified aircraft by airlines using strategic airline planning and aircraft design

May 2022, Noa Zuijderwijk

Delft University of Technology, Delft, The Netherlands

**Abstract**

To reduce the environmental impact of the aviation sector in Europe, climate goals have been set as stated in the *Paris Agreement* [39] and the *European Green Deal* [9]. This reduction can be achieved by fleet replacement with electrified aircraft. Challenging is that electrified aircraft are yet in a conceptual phase and most likely suitable for smaller airline networks. This research presents a study on how regional airlines can strategically adapt to fleet replacement by not-yet-designed electrified aircraft. Earlier research shows interest in integrating strategic airline planning and aircraft design, but the design and operation of electrified aircraft are not yet considered.

A methodology is presented to couple strategic airline planning and electrified aircraft design. In the strategic network and fleet planning model, the operation of electrified aircraft is considered. The electrified aircraft design is provided by the *Initiator* and aircraft configuration options by the *Breguet Range equation*. Based on current network information, this approach considers the adaptation of an airline on not-yet-designed electrified aircraft. Impacts on network performance, such as profit, $CO_2$ emission and operating routes, as well as chosen aircraft are studied.

In this research paper, the methodology is tested with a case study of the airline *SATA Air Açores*. The impact of replacing their current fleet with electrified aircraft on the network performance, development, and aircraft design choices is considered. Furthermore, the impact of airlines' choices and external factors are evaluated. Under the assumptions, the adaption of electrified aircraft seems profitable for the airline and the $CO_2$ emission is highly reduced. A choice for smaller fully-electric and medium-sized hybrid-electric aircraft is presented.

## 1 Introduction

To reduce the environmental impact of the aviation sector in Europe, climate goals have been set as stated in the *Paris Agreement* [39] and the *European Green Deal* [9]. The *Destination 2050* report [40] presents different measures to achieve this goal. One of these measures is to focus on aircraft and engine technologies and replace current kerosene aircraft with electrified aircraft. Electrified aircraft are driven (partly) by electrical battery energy which results in less $CO_2$ emission and thus a reduction in environmental impact. This paper further elaborates on this particular measure. Electrified aircraft can be implemented in the current air transport network by fleet replacement. To accomplish this, airlines should strategically adapt to operate electrified aircraft.

Electrified aircraft are yet in a conceptual phase, but as the specific energy of batteries is lower than that of kerosene, for now only smaller ranges can be reached. Therefore, smaller airline networks are suitable for the introduction of electrified aircraft and the focus of this research is on regional airlines. Since these aircraft are in a conceptual design phase, it is relevant to study the relation between electrified aircraft design and airline planning. This research aims to study how airlines can strategically adapt to fleet replacement by not-yet-designed electrified aircraft. Therefore, strategic airline planning and electrified aircraft design are integrated.

Achieving a combination of these disciplines requires state-of-the-art knowledge, so a literature study on strategic airline planning and the combination with aircraft design is performed and briefly presented in section 1.1. The gaps in the literature and forthcoming challenges are presented in the problem context in 1.2. Thereafter, the contribution of this research and the structure of this paper are provided in section 1.3 and 1.4.

### 1.1 Literature Review

The aim of the literature study is to find earlier research on the combination of strategic airline planning and electrified aircraft design. Therefore, first the strategic airline planning models are studied, followed by the integration of aircraft design.

Strategic airline planning consists of fleet planning and network development [6]. At first, these aspects were treated in separate models. Fleet planning models have the goal to create an optimal fleet planning regarding a known network. A basic version of such a planning model is presented by Schick and Stroup [53]. Later research has evolved to include uncertainties [42, 36, 34, 43, 48, 13, 29] or environmental impact [35].

Network development models aim to find the optimal network for a given aircraft fleet. A basic model is provided by Jaillet et al. [30]. Extensions to the model are made, amongst others, by; Evans et al. [17] who included airport capacity constraints, and Wang et al. [58] who included spill and recapture of passengers.

The aim is to see how airlines can strategically adapt to electrified aircraft, where both network and fleet are yet variable. Therefore, a combination of the fleet planning and network development models is requested. This leads to a network and fleet model [52] where the network development and fleet choice are simultaneously performed. So far, the network and fleet models have not considered the operation of electrified aircraft.

Research presents the integration of strategic airline planning and aircraft design. Crossley et al. [11] desires to determine the appropriate mix for both existing and yet-to-be-designed aircraft and formulates the problem as a "System-of-Systems" design problem. Formulating the problem this way leads to a Mixed-Integer, Non-Linear Programming (MINLP) formulation. Different approaches to the problem have been presented; such as the decomposition approach of multidisciplinary optimization [11, 10] and the traditional MINLP approach for small size problems [37]. Taylor and de Weck [57] showed the benefits of optimizing both the network and aircraft design at the same time and Nusawardhana and Crossley [41] and Davendralingam and Crossley [12] investigated the long term fleet assignment and the impact on aircraft design. Different studies have been done to create an efficient algorithm and various approaches are presented, but not one "best" approach is obtained [24, 25, 26, 46, 47]. Additional details are encountered in later work: Alexandre et al. [3] presented a complex integrated network approach where both the aircraft family of three aircraft designs and the air transport networks are simultaneously optimized. The aircraft design has only incorporated kerosene aircraft and not yet electrified aircraft.

## 1.2 Problem context

The last references show that there is interest in developing integrated airline network and aircraft design models. However, no work has considered the design and operations of electrified aircraft. Therefore, required information on these topics is collected and presented in this section. First, the state-of-the-art, challenges and methods for electrified aircraft design are presented. Followed by the impact on airline operations. Furthermore, the effect of including environmental impact and regional airline regulations is presented.

In this paper, the definition of electrified aircraft is aircraft driven (partly) by electrical energy from batteries. These electrified aircraft can be classified into different groups, the fully-electric and hybrid-electric aircraft. Within the hybrid-electric aircraft, aircraft driven by a battery are serial hybrid-electric and parallel hybrid-electric designs. These types can be distinguished by their degree of hybridization [5, 28]. At this moment, the largest realized electrified aircraft has a capacity of four seats [7]. To serve regional airlines, electrified aircraft with more than four seats are considered, which are not yet brought into reality. The current state-of-the-art for regional electrified aircraft thus consists of conceptual aircraft designs. Different conceptual aircraft designs have been studied and the most challenging aspects turn out to be the feasibility of battery-specific energy, the payload-range trade-off, and the cost estimation.

The current realized battery-specific energy of an aircraft reaches 207 Whr/kg for the Airbus E-Fan [27]. For the future: NAE expects the specific energy to reach 400-600 Whr/kg at pack level by 2035 [38] and NASA predicts a future battery technology that can deliver 400-1000 Whr/kg at pack level [44, 31]. Conceptual aircraft designs often have a required specific energy of 500-750 Whr/kg [55, 19, 4, 32], which is stated optimistic but possibly feasible for the future [59, 14]. Moreover, aircraft designs with a required battery energy of 2000 Whr/kg at pack level are presented [23], but this feasibility should be questioned [20]. Among the potential aircraft designs for regional operations, the fully-electric aircraft require significantly more specific battery energy than hybrid-electric ones with the same passenger capacity. As increasing the specific energy is already challenging, it is more likely for hybrid-electric aircraft to become feasible in the future than fully-electric aircraft, especially for larger aircraft.

In addition, a trade-off occurs between the battery capacity (and thus energy), range, and seats as presented in the conceptual designs of Finger et al. [20]. When it is desired to increase the range of the aircraft, the amount of batteries needs to increase to provide the required energy. This increase in batteries raises the weight of the aircraft and to remain the same maximum take-off weight, fewer passengers can be transported. This is a vice versa process; when it is preferred to transport more passengers either the specific energy of the battery needs to increase, or the range decreases.

Further, as no electrified aircraft in regional sizes have been brought into reality, the aircraft cost definition is challenging. An estimation of costs for electrified aircraft can be made by comparing the ownership cost of vehicles available so far. Smaller-scale aircraft, the Pipistrel Alpha Trainer and the Pipistrel Taurus do have both kerosene and electrified versions. For the Alpha Trainer, the electrified version is around 50% more expensive than the kerosene variant, and for the Taurus, the electrified version is around 16% more expensive [1]. Next to this, an indication of aircraft costs can be given by the cost of electric cars. As electric cars are in a more mature stadium than electrified aircraft, this could indicate the aircraft price in the longer term. When looking at the *Volvo XC40*, the price of a hybrid-electric variant is around 8.5% higher and the fully-electric variant around 9.8% higher than the fuel-based variant [8].

For this research, the *Initiator* can be used to obtain electrified aircraft designs. The *Initiator* is a design synthesis tool developed at the Delft University of Technology and enables the quick generation of an airplane conceptual design [16]. The tool can design kerosene, fully-electric and hybrid-electric aircraft. The relation between aircraft characteristics such as speed, range, required runway, and energy consumption can be obtained. However, this tool requires quite some manual and computational effort and is thus not suitable to be integrated within a strategic airline planning model. It can be used to create an initial set of electrified aircraft designs.

Thereby, one aircraft design can have various configurations regarding the trade-off in battery capacity, range, and seats. Different configurations can be composed by the *Breguet Range equation*, which provides the relation between aircraft size, payload (passenger capacity), and range. Originally, this equation was established for kerosene aircraft, as presented in equation 1. Later, de Vries et al. [15] derived the equation for both hybrid-electric and fully-electric aircraft, presented in equation 2 and 3. As the *Breguet Range equation* only needs a set of equations to create new aircraft configurations, this method can be coupled with a strategic airline planning model. Like this, strategic airline planning and electrified aircraft design can be integrated.

*Breguet Range equation for kerosene aircraft [15]:*

$$R = \eta_1 * \eta_3 * \frac{e_f}{g} * \frac{L}{D} * \ln\left(\frac{W_{OE} + W_{PL} + W_f}{W_{OE} + W_{PL}}\right) \tag{1}$$

*Breguet Range equation for hybrid-electric aircraft [15]:*

$$R = \eta_3 * \frac{e_f}{g} * \frac{L}{D} * \left(\eta_1 + \eta_2 * \frac{\phi}{1-\phi}\right) * \ln\left(\frac{W_{OE} + W_{PL} + W_f + W_b}{W_{OE} + W_{PL} + W_b}\right) \tag{2}$$

*Breguet Range equation for fully-electric aircraft [15]:*

$$R = \eta_2 * \eta_3 * \frac{L}{D} * \frac{E_{0\_tot}}{W_{OE} + W_{PL} + W_b} \tag{3}$$

Where $R$ is the maximum range $[m]$, $\eta_1, \eta_2$ en $\eta_3$ are conversion or transmission efficiencies $[-]$, $e_f$ and $e_b$ the specific fuel and battery energy $[J/kg]$, $g$ the gravitational acceleration $[m/s^2]$, $L/D$ the lift over drag ratio $[-]$, $W_{OE}$ the operating empty weight of the aircraft without batteries $[N]$, $W_{PL}$ the payload weight $[N]$, $W_f$ the fuel weight $[N]$, $W_b$ the battery weight $[N]$, $\phi$ the supplied power ratio of the battery $[-]$ and $E_{0\_tot}$ the total energy at the start $[GJ]$.

Next to the aircraft design, the airline network should integrate the operations of electrified aircraft. The main difference in operating electrified aircraft is the charging operation. Charging operations influence the turnaround time and the turnaround costs. The impact does depend on the method of charging. Charging can be done by a Battery Recharging Station (BRS) which is similar to the current refueling stations or by a Battery Swapping Station (BSS) which swaps the empty batteries for charged ones [45]. As the charging speed of the BRS at this moment leads to too long charging times [49, 21], this method is currently unfit for electrified airport operations. As a result, the BSS is the feasible option now and research in literature has been focused on this method or a combination of both methods [45, 33, 50, 51]. Schmidt et al. [54] presented a methodology for turnaround time estimation using the BSS method. A hybrid-electric aircraft, the SUGAR Volt, and a fully-electric aircraft, the Ce-liner, are compared with a future version of a conventional kerosene aircraft, the A320-2035. Within the methodology, the turnaround times are formed by different processes such as (de-)boarding, cleaning, and refueling, and the critical time path for these processes is obtained as the turnaround time. As the complete turnaround time from landing until take-off is highly network dependent, it is interesting to obtain the time differences in operating conventional kerosene aircraft and electrified aircraft rather than the exact turnaround times. The time differences between kerosene and electrified aircraft are caused by the refueling and recharging time. In this paper, the refueling and recharging are combined in the *reloading* of an aircraft. The reloading time presents the difference in turnaround time without reloading (thus refueling and/or recharging) and with reloading. For regional aircraft sizes and the BSS method, the reloading time for kerosene aircraft can be estimated at 5 minutes, for fully-electric aircraft at 10 minutes, and 25 minutes for hybrid-electric aircraft. Note that these times show the difference in critical times and do not have to equal actual recharging or refueling times. Cost information on aircraft recharging is scarce in the literature, but because the energy price varies during the day, the time of charging will impact the turnaround costs. However, in strategic airline planning, no schedule is generated. Therefore, the varying charging price over the day can not be taken into account.

Thereby, especially at the start of implementing electrified aircraft, it is likely that the charging facilities are only available at a few airports. Due to this varying availability, electrified aircraft can not be charged at every airport, and thus should reach a charging facility within its range. For conventional aircraft, refueling is often possible at every airport and the network can be translated into single flights. For electrified aircraft, these single flights should be replaced by routes, starting and ending at a charging facility.

Lastly, the focus is on regional airlines adapting to electrified aircraft. Two important network aspects are the assessment of environmental impact and the implementation of regulations.

The environmental impact can be a network performance indicator. The air industry brings along different emissions, where carbon dioxide emission is the most common measure of environmental impact. The amount of emitted $CO_2$ can be related to the amount of kerosene burned. The emission of 1 kg kerosene is estimated at 3.11 kg $CO_2$ [60]. With the goal to reduce environmental impact, governments can introduce a monetary climate tax. Grobler et al. [22] give an indication of the cost of emission, divided into different types of emissions and types of impact. The global aggregate climate metrics for carbon dioxide is set to be on average $45 per tonne $CO_2$, which results in €0.041 per kg $CO_2$.

Further, regional airlines can be part of a Public Service Obligation (PSO) [56]. A PSO occurs when air transport services are not profitable but vital for the economic and social development of a region. To ensure connectivity to these regions, the government may award financial compensation to the carrier that operates this route in return for compliance with the PSO. Generally, the government provides the subsidy to one single carrier and so this airline is protected from competition during the PSO period. The government can set a minimum service frequency or a minimum capacity for connections between airports.

### 1.3 Contribution

This paper studies how an airline can strategically adapt to electrified aircraft and what the relation is between electrified aircraft design and airline network development. Therefore, a strategic network and fleet model is created where the operation of electrified aircraft is considered. Subsequently, a methodology is presented to couple the electrified aircraft design and obtain the most suitable combination of electrified aircraft configuration and network development. Both design and operations of electrified aircraft have not been considered in strategic airline planning models before, so this paper will contribute to assess the adaptation of electrified aircraft.

### 1.4 Structure

The structure of this paper is as follows. This first section presented the introduction to the topic, the literature review, and the problem context. Section 2 presents the methodology of this research, presented in a flowchart, and elaborate upon the different elements. Section 3 introduces the case study which is the airline network of SATA Air Açores. Section 4 presents the results and various scenarios. Section 5 reflects on the results and presents conclusions. A discussion on this research and recommendations for future research are provided in section 6.

## 2 Methodology

This research aims to see how airlines can adapt to fleet replacement by electrified aircraft and present a methodology on how strategic airline planning and electrified aircraft design can be connected. Since the impact on both network development and fleet choice is desired, a network and fleet planning model is chosen as the strategic model. Electrified aircraft designs are provided by the *Initiator* and different aircraft configurations can be obtained by varying relations in the *Breguet Range equation*. Aircraft configuration can be integrated into the strategic planning model as this requires only a set of equations.

The methodology on how to integrate aircraft configuration is presented in a flowchart in Figure 1. The required information consists of network information and an electrified aircraft database. The network information can be obtained by analyzing the current airline network and the electrified aircraft database can be set by the *Initiator*. Then a strategic network and fleet model is established where the operation of electrified aircraft is considered. In an extension of this model, other aircraft configurations of the aircraft given in the database can be studied and configurations contributing to the airlines objective are presented. The proposed aircraft configurations are evaluated and one aircraft configuration can be selected to be included as a new aircraft in the aircraft database. When a new aircraft is added to the aircraft database, again the network and fleet model is performed and other aircraft configurations are studied. This iteration continues until no new aircraft configurations contribute to the objective. Then a final set of aircraft is reached. For this final set of aircraft, the adaptation of the network to electrified aircraft can be studied by looking at the network performance, the network development, and the chosen aircraft configurations.

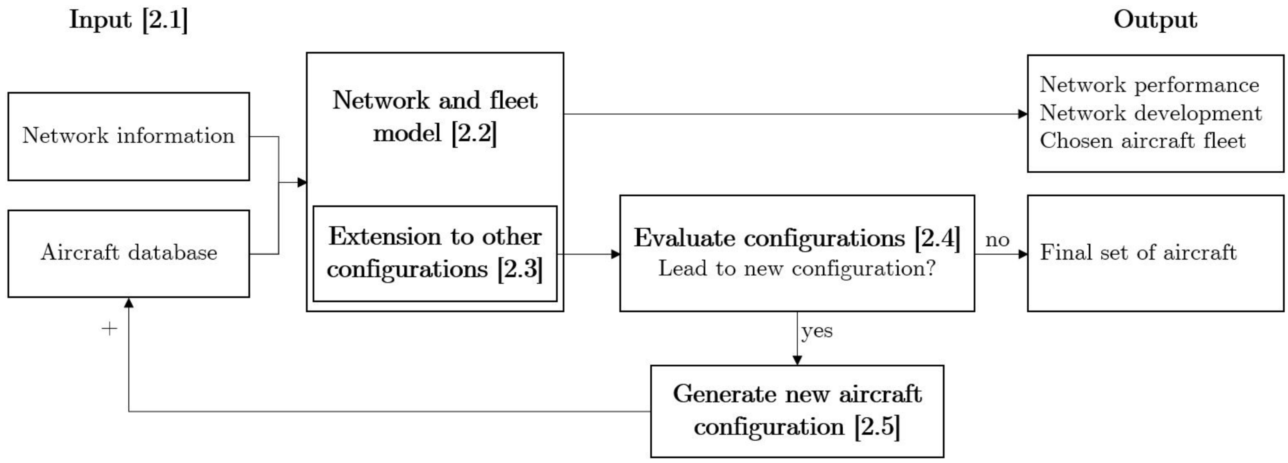



Figure 1: Flowchart methodology

With this approach, every iteration a more profitable combination between electrified aircraft designs and network development can be obtained. The different elements in the flowchart are elaborated upon in the following sections. The required input is discussed in section 2.1. The network and fleet model in section 2.2. Section 2.3 presents the extension to evaluate other aircraft configurations. Lastly, the evaluation of proposed aircraft configurations and the generation of a new aircraft for the database are presented in section 2.4 and 2.5.

## 2.1 Input

The required input consists of network information and an initial aircraft database. This information is collected in an Excel file. The demanded information is elaborated upon in this section.

The network is given by the airports. Airports have a name, often provided by the ICAO or IATA code, and a maximum runway size. Further, the availability of refueling facilities and possible charging facilities should be provided. Next to the airport characteristics, the distance and demand for each airport pair are requested. Other airport information is the maximum time aircraft can be operated per day, which is referred to as the *maximum block time*.

Besides the airport information, some general information should be given. Starting with the period for which the planning is created. This could be one day, a week, or even multiple years. This period is given in days. As it is unlikely that all future flights will be completely filled, a *load factor* can be set, which causes the future flights to have an average occupation percentage. Also, the airline could be part of a PSO, as discussed in section 1.2, and minimum capacity and frequency per connection are an optional input.

Revenue can be defined in yield by one value per passenger-kilometer for the entire network, or in different values per airport pair. In the network, passengers can have an extra stop between their origin and destination. When having a stop, the passenger does not have to (de-)board the aircraft, yet it can be inconvenient. Therefore, the yield for having an extra stop can be multiplied by the *stop factor*. This *stop factor* is a value between 0 and 1 and thus reduces the yield. Furthermore, passengers may have a transfer. This requires the passengers to (de-)board another aircraft. As this is inconvenient, a *transfer factor*, between 0 and 1, can be set to multiply (and thus reduce) the yield.

Furthermore, the available aircraft for the network should be provided in the initial aircraft database. For this set of aircraft, various information is required such as the number of seats, speed, required runway, and maximum range. Information on the battery and fuel capacity is given by the maximum battery energy and fuel capacity for the mission, battery energy and fuel consumption per kilometer, and battery energy and fuel consumption per landing and take-off cycle. Furthermore, time estimations for turnaround without reloading (thus refueling and recharging), reloading, and the landing and take-off cycle are requested.

For the costs, the ownership costs per aircraft and operating costs per flight are considered. Ownership costs are defined per aircraft per day. Operating costs are determined per aircraft per flight leg and can be divided into fixed costs, time-based costs, distance-based costs, fuel costs and battery energy costs. Fixed costs represents costs such as airport use, landing rights, and parking fees and depends on the aircraft type and the number of flights. Further, time-based costs are costs that are defined per hour and represent costs such as cabin and flight crew. Distance-based costs depend on the flown kilometers and represent costs such as maintenance. Besides these costs, the cost regarding $CO_2$ tax and costs for consumed fuel and battery energy are added to the operating costs. Therefore, values for the $CO_2$ emission per kg kerosene, the $CO_2$ tax in €/kg, fuel cost and energy cost should be provided.

## 2.2 Network and fleet model

The network and fleet model is based on existing network and fleet models but considers the operation of electrified aircraft. The input of the model is presented in section 2.1. For the network and fleet model, it is important to define the objective, as the model will develop the network and fleet choice towards the objective. For an airline, the objective is often to maximize profit but an alternative objective such as maximizing revenue, minimizing cost, or minimizing $CO_2$ emissions can be chosen as well. The objective is maximized by assigning passengers to flights and assigning flights to aircraft. The model can assign passengers to direct flights or transfer flights. The results of the model present the network performance in terms of revenue, cost, and emissions, present the network development in terms of flights, frequencies, and passenger flows, and present the fleet choice.

The network and fleet model considers the operation of electrified aircraft. Compared to the operation of kerosene aircraft, the electrified aircraft need to be recharged. It is assumed that the recharging of aircraft is done by a battery swap method, as presented in the Problem context. Further, it is identified that if not every airport has a charging facility, the network should be defined in routes instead of single flights. Routes consist of one or multiple subsequent flights which start and end at a charging facility. To implement routes instead of single flights in the network and fleet model, routes and their characteristics are defined.

Routes thus consist of a set of one or multiple flights. The first and the last airport on the route should have a charging facility but do not have to be the same airport. Possible airports between the first and last airports are airports without a charging facility and can not be equal the previous airport on the route. For the routes, all possible combinations within these conditions are considered. An illustration the route establishment is presented in Figure 2. In this illustration, the network is given by airport A, B, and C and only airport A has a charging facility. The routes in this example are presented on the right. It can be noted that routes can become quite long, thus a maximum route size is set which defines the maximum number of flights per route. Furthermore, the routes with a total distance longer than the maximum aircraft range and routes with airports with a smaller minimum runway than the required minimum aircraft runway are not taken into account. A set of routes is obtained and information on the airports on the route, the number of flights, and the total distance is saved. It is assumed that passengers can only transfer to first and last airports on the route, thus at airports with a charging facility.

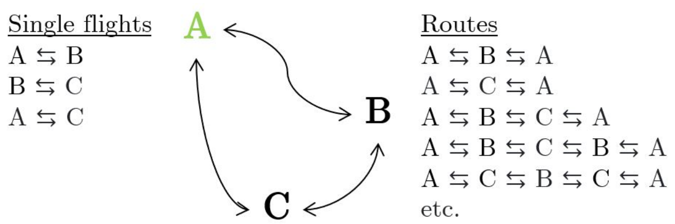



Figure 2: Illustration of routes versus single flights

To elaborate on the network and fleet model, the notation is presented. The following **sets** are present in the model formulation. Note that a *flight* is used for a single flight and a *route* for a set of flights.

- $\boldsymbol{N}$: set of airports, indexed by:
  - $i$ : used for flight start airport
  - $j$ : used for flight end airport
  - $a$: used for demand origin airport
  - $b$: used for demand destination airport
- $\boldsymbol{R}$: set of routes, indexed by:
  - $r$: used for route

- $m$: used for transfer route

- $\boldsymbol{K}$: set of aircraft types, indexed by $k$
- $\boldsymbol{P}$: set of PSO requirements for direct flights per airport pair, indexed by $s$

To interpret the formulation, abbreviations and explanations of parameters are stated.

- $LF$ : load factor
- $BT$ : maximum block time
- $TAT$ : turnaround time
- $LTOt$ : landing and take-off time
- $SF$ : stop factor
- $TF$ : transfer factor
- $period$ : time span in days
- $PSOcap_s$ : minimum PSO capacity on flight $s$
- $PSOfreq_s$ : minimum PSO frequency on flight $s$

Passengers in this model are allocated to routes instead of single flights. To do this, additional parameters are set to connect demand and flights to routes. These binary parameters are:

- $R1^r_{i,j}$, this equals 1 if flight $i$ to $j$ is part of route $r$
- $R2^r_{a,b}$, this equals 1 if route $r$ can transport passengers from $a$ to $b$
- $R3^r_{a,b i,j}$, this equals 1 if on route $r$, travelling from $a$ to $b$, flight $i$ to $j$ is taken
- $R4^{r,m}_{a,b}$, this equals 1 if route $r$ followed by route $m$ can transport passengers from $a$ to $b$
- $stops^r_{a,b}$, $stops^{r,m}_{a,b}$, the number of extra stops on route $r$ (and $m$) for a passenger travelling from $a$ to $b$
- $SR^r_s$, this equals 1 if route $r$ is contributing to the PSO requirement $s$

As the model assigns routes to aircraft, the performance of each aircraft per route needs to be determined. First of all, the required fuel and battery energy per route per aircraft type are determined in equation 4 and 5. If the required fuel and battery energy can be stored in the aircraft and the runway size complies, the route can be flown by the aircraft type and parameter $AR$ is adjusted, see equation 6. When the route can be flown by the aircraft type, the other performance values, such as emission, time, and cost are determined as presented in equation 7, 8 and 9. Note that per route, the aircraft is reloaded (thus recharged and/or refueled) once and the cost definition shows the operating cost.

$$fuel^r_k = fuel\_per\_km_k * distance_r + fuel\_per\_LTO_k * flights_r \tag{4}$$
$$battery^r_k = battery\_per\_km_k * distance_r + battery\_per\_LTO_k * flights_r \tag{5}$$
$$AR^r_k = 10000 \quad \text{if route } r \text{ can be flown by aircraft } k\text{, else value is 0} \tag{6}$$
$$emission^r_k = emission\_fuel * fuel^r_k \tag{7}$$
$$time^r_k = distance_r / speed_k + (LTOt + TAT) * flights_r + reload\_time_k \tag{8}$$
$$\begin{aligned} cost^r_k = & cost\_trip_k * flights_r + cost\_hour_k * time^r_k + cost\_km_k * distance_r \\ & + fuel\_cost * fuel^r_k + energy\_cost * batt^r_k + CO_2\_tax * emission^r_k \end{aligned} \tag{9}$$

Based on existing network and fleet models and the additional model elements, a Linear Programming (LP) model is built to optimize the network to the objective function. The decision variables, objective function, and sets of constraints are presented in the following LP formulation.

**Decision variables**

- $ac_k$ : Amount of aircraft needed from type $k$
- $z_k^r$ : Frequency of aircraft $k$ on route $r$ in given period
- $x_{a,b}^r$ : Number of passengers that go from airport $a$ to $b$ on route $r$ in given period
- $w_{a,b}^{r,m}$ : Number of passengers that go from airport $a$ to $b$ on route $r$ followed by route $m$ in given period

**Objective function**
The objective function (OF) can be defined based on the objective of the airline. Generally, the objective of an airline is to maximize profit, thus maximizing the revenue minus cost (see equation 10). The formulation for revenue is given in equation 11 and for cost in equation 12.

$$\text{OF} = \textit{maximize}\ \text{profit} = \textit{maximize}\ \text{Revenue - Cost} \tag{10}$$

$$\text{Revenue} = \sum_{r\in \boldsymbol{R}}\sum_{a\in \boldsymbol{N}}\sum_{b\in \boldsymbol{N}}[yield_{a,b} * dist_{a,b} * SF^{stops^r_{a,b}} * x^r_{a,b} + \sum_{m}[yield_{a,b} * dist_{a,b} * TF * SF^{stops^{r,m}_{a,b}} * w^{r,m}_{a,b}]] \tag{11}$$

$$\text{Cost} = \sum_{k\in \boldsymbol{K}}[\sum_{r\in \boldsymbol{R}}[cost^r_k * z^r_k] + cost\_ownership_k * ac_k] \tag{12}$$

**Set of constraints**
Set of constraints *C1*: the total sum of passengers that travel from airport $a$ to $b$ should be smaller or equal to the demand from airport $a$ to $b$.

$$\sum_{r\in \boldsymbol{R}}[x^r_{a,b} + \sum_{m} w^{r,m}_{a,b}] \leq demand_{a,b} \qquad \forall a,b \in \boldsymbol{N} \tag{13}$$

Set of constraints *C2*: number of passengers that travel from $a$ to $b$ on route $r$ is less or equal to the demand from $a$ to $b$ if route $r$ can serve demand from $a$ to $b$.

$$x^r_{a,b} \leq demand_{a,b} * R2^r_{a,b} \qquad \forall a,b \in \boldsymbol{N}, r \in \boldsymbol{R} \tag{14}$$

Set of constraints *C3*: number of passengers that travel from $a$ to $b$ on route $r$ followed by route $m$ is less or equal to the demand from $a$ to $b$ if route $r$ and $m$ combined can serve demand from $a$ to $b$.

$$w^{r,m}_{a,b} \leq demand_{a,b} * R4^{r,m}_{a,b} \qquad \forall a,b \in \boldsymbol{N}, r,m \in \boldsymbol{R} \tag{15}$$

Set of constraints *C4*: the flow of passengers from airport $i$ to $j$ on route $r$ should be less or equal to the total seats on aircraft flying from airport $i$ to $j$ on route $r$.

$$\sum_{a\in \boldsymbol{N}}\sum_{b\in \boldsymbol{N}}[x^r_{a,b} * R3^r_{a,bi,j} + \sum_{m}[w^{r,m}_{a,b} * R3^r_{a,end_r i,j} * R4^{r,m}_{a,b}] + \sum_{m}[w^{m,r}_{a,b} * R3^r_{start_r,bi,j} * R4^{m,r}_{a,b}]] \leq \sum_{k}[]R1^r_{i,j} * z^r_k * seats_k * LF] \qquad \forall r \in \boldsymbol{R}, i,j \in \boldsymbol{N} \tag{16}$$

Set of constraints *C5*: aircraft can only fly route $r$ with aircraft type $k$ if possible

$$z^r_k \leq AR^r_k \qquad \forall k \in \boldsymbol{K}, r \in \boldsymbol{R} \tag{17}$$

Set of constraints *C6*: for all start and end (charging airports), #aircraft landing = #aircraft take off

$$\sum_{r}[\sum_{i\in \mathbf{N}}[R1^r_{i,c}] * z^r_k] = \sum_{m}[\sum_{j\in \mathbf{N}}[R1^r_{c,j}] * z^m_k] \qquad \forall k \in \boldsymbol{K}, c \in \boldsymbol{N}_{charging=possible} \tag{18}$$

Set of constraints *C7*: maximum time an aircraft is used should be smaller or equal to the total block time

$$\sum_{r\in \boldsymbol{R}}[time^r_k * z^r_k] \leq BT * ac_k * period \qquad \forall k \in \boldsymbol{K} \tag{19}$$

Set of constraints *C8*: fulfill PSO requirements. *C8a* for frequency requirements and *C8b* for capacity requirements

$$\sum_{r \in \boldsymbol{R}} [SR_s^r * \sum_{k \in \boldsymbol{K}} z_k^r] \geq PSOfreq_s \qquad \forall s \in \boldsymbol{P} \tag{20}$$

$$\sum_{r \in \boldsymbol{R}} [SR_s^r * \sum_{k \in \boldsymbol{K}} [seats_k * z_k^r]] \geq PSOcap_s \qquad \forall s \in \boldsymbol{P} \tag{21}$$

Solving this LP model, the outcome regarding network performance, network development, and fleet choice can be obtained. The optimization can require quite some time. As this is a strategic model, a good estimation of the objective value is required rather than the exact outcome. Therefore, a time limit for the optimization can be set in the input file.

## 2.3 Extension to other aircraft configurations

An extension to the Network and fleet model is created to evaluate other aircraft configurations. The goal is to study other aircraft configurations to enhance network performance. First, the method to define other aircraft configurations is presented, followed by the LP model extension.

For electrified aircraft, the payload-range trade-off is an important design aspect. This trade-off leads to different configurations of one aircraft design. These different configurations can be created by using the *Breguet Range equation*, presented in section 1.2. When only the payload-range trade-off is considered for an aircraft design, the maximum take-off weight and the design point are assumed to be constant. In this situation, the efficiencies ($\eta_1, \eta_2, \eta_3$), the battery- and fuel-specific energy ($e_b, e_f$), the lift over drag ratio ($L/D$), the supplied power ratio ($\phi$) and the operating empty weight ($W_{OE}$) are constant as well. Varying elements in the equations will then only be the range ($R$), payload weight ($W_{PL}$), and the energy given in $W_f$, $W_b$ and $E_{0\_tot}$. To illustrate, the *Breguet Range equations* are again presented in equation 22 and 23, but now constant parameters are given in red en varying parameters in blue. Only the equations for electrified aircraft are presented since the focus is on electrified aircraft design.

*Breguet Range equation for hybrid-electric aircraft [15]:*

$$R = \eta_3 * \frac{e_f}{g} * \frac{L}{D} * (\eta_1 + \eta_2 * \frac{\phi}{1-\phi}) * \ln(\frac{W_{OE} + W_{PL} + W_f + W_b}{W_{OE} + W_{PL} + W_b}) \tag{22}$$

*Breguet Range equation for fully-electric aircraft [15]:*

$$R = \eta_2 * \eta_3 * \frac{L}{D} * \frac{E_{0\_tot}}{W_{OE} + W_{PL} + W_b} \tag{23}$$

It is chosen to change the aircraft configuration by one row of seats per iteration. If one row of seats is added to the aircraft, the payload weight increases with the weight of this additional row of seats. To keep the maximum take-off weight constant, the energy weight (both $W_f$ and $W_b$) should decrease. The new values of $W_f$, $W_b$ and $E_{0\_tot}$ can be defined by solving equations 24, 25 and 26[15]. Again, constant values are presented in red while varying values are in blue.

$$W_{energy\_tot} = W_b + W_f \tag{24}$$

$$W_b = \frac{e_b}{g} * \phi * E_{0\_tot} \tag{25}$$

$$W_f = \frac{e_f}{g} * (1 - \phi) * E_{0\_tot} \tag{26}$$

With the new values for $W_f$, $W_b$ and $E_{0\_tot}$, the range for this aircraft configuration is calculated by the *Breguet Range equation*. If the payload increases and thus the total energy weight reduces, the range reduces as well. For a decreased payload, it is vice versa. As the maximum take-off weight and design point are constant, other aircraft characteristics do not change. If it is assumed that the cost values are constant for different configurations, only a trade-off between range and passenger capacity is obtained for a new aircraft configuration.

Note that the aircraft configuration is limited by the aircraft exterior, and a maximum number of seats can fit in the aircraft. When this limit is reached, no aircraft configurations with more seats can be established using this approach.

To compare the performance of other aircraft configurations to the original aircraft configuration, an extension to the network and fleet model is created. In this extended model, it is possible to evaluate other configurations with one extra row or one less row of seats to the original aircraft. The most profitable configuration is chosen per route (per aircraft type). This leads to two new decision variables: $extra\_row^r_k$ and $less\_row^r_k$. So, an aircraft can have a configuration with one extra row on one route (for all frequencies on this route) and a configuration with one less row on another route. Now, differences to the network and fleet model are presented.

First of all, the trade-off between payload and range impacts the routes that can be flown. Removing one row from the aircraft extends the aircraft range. Due to this, routes within this extended range can be flown with decreased capacity but not with the original aircraft capacity. On the other hand, adding one row to the aircraft diminishes the aircraft range. Due to this, some routes are not available anymore for aircraft with an increased capacity. To define which routes can be flown with which configuration, performance calculations such as presented in equation 4-9, should be defined for new aircraft configurations. This leads to two additional parameters $AR\_less$ and $AR\_extra$:

- $AR\_less^r_k$, this equals 1 if route $r$ can only be flown by aircraft $k$ when having one less row
- $AR\_extra^r_k$, this equals 10000 if route $r$ can be flown by aircraft $k$ when having one extra row

A set of constraints *C9a*, presented in equation 28, makes sure that if a route can only be flown by an aircraft configuration with one less row, this configuration is chosen. A set of constraints *C9b*, presented in equation 29, ensures that an extra row can only be added if the aircraft can still fly this route.

The other change to the model is the capacity change. This impacts the number of passengers that can be transported and is implemented in the set of capacity constraints *C4*, presented in equation 27.

To guarantee that the same configuration is chosen for every frequency per aircraft type per route, a set of constraints *C10* is added, presented in equation 30-34. For this set of constraints, a binary variant of both decision variables *extra_row* and *less_row*, and a variable to state no change in rows: *row_0* and its binary variant are required.

With the new model elements, the LP model for the extended network and fleet model is presented. Note: only the differences are presented.

**Decision variables**

- $extra\_row^r_k$ : one row is added for all frequencies of aircraft type $k$ on route $r$
- $less\_row^r_k$ : one row is removed for all frequencies of aircraft type $k$ on route $r$
- $row\_0^r_k$ : no row changes for all frequencies of aircraft type $k$ on route $r$
- $extra\_row\_binary^r_k$ : binary value of $extra\_row^r_k$
- $less\_row\_binary^r_k$ : binary value of $less\_row^r_k$
- $row\_0\_binary^r_k$ : binary value of $row\_0^r_k$

**Sets of constraints**

Set of constraints *C4*: flow from airport $i$ to $j$ on route $r$ should be less or equal to the total seats on aircraft flying from airport $i$ to $j$ on route $r$

$$\sum_{a\in \boldsymbol{N}}\sum_{b\in \boldsymbol{N}}[x^r_{a,b} * R3^r_{a,bi,j} + \sum_m w^{r,m}_{a,b} * R3^r_{a,end_r i,j} * R4^{r,m}_{a,b} + \sum_m w^{m,r}_{a,b} * R3^r_{start_r,bi,j} * R4^{m,r}_{a,b}] \leq \sum_k R1^r_{i,j} * (z^r_k * seats_k + (extra\_row^r_k - less\_row^r_k) * seats\_per\_row_k) * LF \qquad \forall r \in \boldsymbol{R}, i,j \in \boldsymbol{N} \tag{27}$$

Set of constraints *C9a*: if a route can only be flown by an aircraft configuration with one less row, make sure this configuration is chosen

$$z^r_k \leq less\_row^r_k \qquad \forall r,k \in AR\_less^r_k = 1 \tag{28}$$

Set of constraints *C9b*: make sure that a route can only be flown by a configuration with one extra row if the range is still feasible

$$extra\_rows^r_k \leq AR\_extra^r_k \qquad \forall k \in \boldsymbol{K}, r \in \boldsymbol{R} \tag{29}$$

Set of constraints *C10a/C10b/C10c/C10d/C10e*: per route per aircraft type all frequencies have extra, less or not changed number of rows. Where $M$ » z and »#ac

$$extra\_row\_binary_k^r + less\_row\_binary_k^r + row\_0\_binary_k^r = 1 \qquad \forall k \in \boldsymbol{K}, r \in \boldsymbol{R} \tag{30}$$

$$extra\_row_k^r + less\_row_k^r + row\_0_k^r = z_k^r \qquad \forall k \in \boldsymbol{K}, r \in \boldsymbol{R} \tag{31}$$

$$extra\_row_k^r \leq M * extra\_row\_binary_k^r \qquad \forall k \in \boldsymbol{K}, r \in \boldsymbol{R} \tag{32}$$

$$less\_row_k^r \leq M * less\_row\_binary_k^r \qquad \forall k \in \boldsymbol{K}, r \in \boldsymbol{R} \tag{33}$$

$$row\_0_k^r \leq M * row\_0\_binary_k^r \qquad \forall k \in \boldsymbol{K}, r \in \boldsymbol{R} \tag{34}$$

The result of the extended LP model presents aircraft configurations that are enhancing the network performance. It indicates which aircraft configuration is profitable per aircraft type per route. An example of the model outcome is presented in Table 1.

Table 1: Example of output of extension to other configurations

| **aircraft** | **one less row** | **one extra row** | **original rows** | **sum** |
|---|---|---|---|---|
| FE20 | 0 | 4 | 4 | 8 |
| FE28 | 2 | 3 | 0 | 5 |
| FE48 | 4 | 2 | 0 | 6 |

In the model, for every aircraft type, the configuration is chosen per route. In this table, per aircraft type, the number of routes where a configuration is chosen is presented. Thus for this example, for aircraft *FE20* the configuration of having one less row is not chosen, the configuration of having one extra row is chosen for 4 routes and the original configuration is chosen for 4 routes. In the next block in the flowchart Evaluate proposed configurations, one aircraft configuration is chosen to be included in the aircraft database.

Besides the selected configurations, the outcome also gives information on the network performance, development, and fleet choice, but this can not be stated as true. Since the choice for configuration is determined per aircraft type per route, this leads to the option to switch the aircraft configuration for every different route that is flown, which is not feasible in reality. Therefore, the output can be used as a comparison with the network and fleet model, but to say anything about the "real" performance, the network and fleet model should be used.

## 2.4 Evaluate proposed configurations

The next step in the flowchart is to select a new aircraft configuration and add this to the aircraft database. Per iteration, one new aircraft can be added. The new aircraft name is based on the original aircraft and the modification in rows, thus for example aircraft *FE20* with a configuration of one extra row will become *FE20+1*, and with one less row *FE20-1*. When multiple aircraft configurations are proposed in the output of the extension model, like the output presented in Table 1, one should be chosen. The choice is made by the following algorithm, illustrated in Figure 3. The column *one less row* is now presented by *-1*, *one extra row* by *+1*, and *sum* by $\sum$. The column *original rows* is not shown.

1. Skip all the aircraft configurations which are outside the aircraft limitations or already present in the aircraft database.
2. Choose the aircraft configuration which is most often chosen. Thus the highest number in columns [*-1*] and [*+1*].
3. When multiple aircraft are selected in step 2, the aircraft which is relatively most chosen, with the highest [*-1*]/[$\sum$] or [*+1*]/[$\sum$] of the aircraft configurations found in step 2 is chosen.
4. When again multiple aircraft configurations are selected, just the first one (row-column) is chosen.

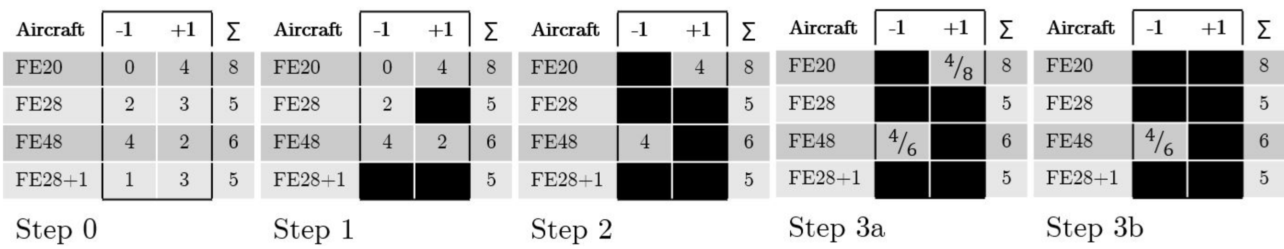



Figure 3: Illustration of the algorithm to choose a new aircraft configuration

### 2.5 Generate a new aircraft configuration

In section 2.4, a new aircraft configuration to add to the aircraft database is selected. To include this new configuration, the aircraft characteristics should be known. As discussed before, the exterior design and maximum take-off weight of the aircraft will be constant which causes most of the aircraft characteristics to be constant as well. The new configuration has new values for the payload, the maximum fuel weight, the maximum battery energy, and the maximum range. These values are determined as presented in section 2.3. These values need to be collected together with the new aircraft name and the new number of seats.

The new aircraft configuration is added to the aircraft database to run both the network and fleet model as the extension to evaluate other configurations. The network performance, development, and chosen fleet can be obtained, and interesting aircraft configurations are suggested for each iteration. When the algorithm presented in section 2.4 is not able to select a new aircraft configuration to add to the aircraft database, a final set of aircraft configurations is reached. The network performance, network development, and fleet choice with this final set of aircraft configurations presents the final network choice.

## 3 Case study

The network of SATA Air Açores is implemented to test the presented methodology. SATA Air Açores is a regional airline and part of the SATA network which can be divided into SATA Air Açores and SATA International. SATA Air Açores is established in 1941 in Ponta Delgada to connect the isolated regions of Azoren and provides flights between these islands and a connection to the larger airline network(s) [2]. Serving these isolated regions is not profitable for the airline and therefore the government has chosen to set PSO regulations and subsidize the airline for operating specific connections.

In this part, the current situation is presented by its network and fleet in section 3.1 and 3.2. To connect electrified aircraft design and strategic airline planning, additional information regarding the design and operation of electrified aircraft is required and presented in section 3.3. Further assumptions are stated in section 3.4.

### 3.1 Network

The network consists of nine islands in the Azoren, presented in Figure 4. The corresponding airports and their specifications are given in Table 2. The network is connected to the larger network of SATA International by the airports Ponta Delgada, Terceira, and occasionally Horta.


Figure 4: Map of SATA Air Açores network [2]

Table 2: SATA Air Açores Airports

| Location | ICAO code | IATA code | Refuel facility | Runway length |
|---|---|---|---|---|
| Santa Maria | SMA | LPAZ | Yes | 3048 m |
| San Miguel - Ponta Delgada | PDL | LPPD | Yes | 2323 m |
| Terceira | TER | LPLA | Yes | 3310 m |
| Graciosa | GRW | LPGR | No | 1268 m |
| São Jorge | SJZ | LPSJ | No | 1270 m |
| Pico | PIX | LPPI | Yes | 1655 m |
| Faial – Horta | HOR | LPHR | Yes | 1595 m |
| Flores | FLW | LPFL | No | 1342 m |
| Corvo | CVU | LPCR | No | 761 m |

In the network, refueling is not possible at every airport. Therefore, this network already consists of routes instead of single flights. At the airports, an average turnaround time of 30 minutes is obtained, including refueling the aircraft. The flight times, including the landing and take-off times and excluding turnaround times, are given per city pair per aircraft type.

The revenue of the network is gained by the yield of passengers. The yield depends on the city pair and is given in yield per passenger per kilometer per city pair. For the distance, the great circle distance between the origin and destination airport is inserted.

For the network, PSO requirements have been established for multiple network aspects; minimum values for frequency, capacity, and cargo weight are set. These values are set for direct flights between airport pairs. The financial compensation is not fixed and determined afterwards. Therefore, this compensation is not included in the network and fleet model, which likely results in negative profit values. Furthermore, the airline network is located in an outermost region, which is at this moment excepted from climate tax.

## 3.2 Fleet

The flights between the islands of Azoren are currently covered by two turboprop aircraft from De Havilland Canada and Bombardier Aerospace. The two aircraft and their specifications are presented in Table 3.

Table 3: SATA Air Açores Fleet

| **Aircraft** | **Q200** | **Q400** |
|---|---|---|
| **Type** | DHC-8-200 Dash 8 / 8Q | DHC-8-400 Dash 8Q |
| **Seats (max)** | 37 | 80 |
| **Range (max)** | 1839 km | 2656 km |
| **Speed (max)** | 535 km/h | 667 km/h |
| **Required runway** | 974 m | 1431 m |
| **Ceiling** | 7620 m | 7620 m |
| **Maximum fuel weight** | 2500 kg | 5000 kg |
| **Fleet size** | 2 | 4 |

Other important aspects of the fleet are the fuel consumption per kilometer and per landing and take-off cycle. These values are provided by the *Initiator*, presented in section 1.2, for kerosene aircraft.

The cost of operating these aircraft is provided in the time-based cost. Yet the cost does not only contain time-based costs, but also ownership and fixed costs. Therefore, the given cost is divided into ownership cost, fixed cost, and variable cost per hour by taking the average division for regional passenger airlines established by FAA [18]. This leads to the cost estimation presented in Table 4. Note that these costs exclude fuel and energy costs.

Table 4: Cost of fleet

| | cost/day [€] | cost/trip [€] | cost/hour [€] |
|---|---|---|---|
| **Q200** | 4167 | 1312 | 1638 |
| **Q400** | 6596 | 1679 | 2625 |

### 3.3 Operating electrified aircraft

For electrified aircraft, the design and operation are implemented. Starting with the aircraft design where the initial electrified aircraft database is established by the *Initiator*. The created set of aircraft is inspired by the current fleet of regional airlines and opportunities in electrified aircraft design and presented in Table 5. The database consists of 3 fully-electric aircraft and 5 hybrid-electric aircraft. It can be obtained that the hybrid-electric aircraft can reach a higher passenger capacity and requires a lower battery-specific energy for their 28- and 48-seat aircraft. Note that only a fraction of the specifications is given, more required information can be found in Appendix A.1, Table 11.

Table 5: Initial electrified aircraft database

| **Fully-electric** | **Hybrid-electric** |
|---|---|
| **FE20**: 20 seats, 400 km range, $e_b$ = 500 Whr/kg | **HE20**: 20 seats, 400 km range, $e_b$ = 500 Whr/kg |
| **FE28**: 28 seats, 1036 km range, $e_b$ = 700 Whr/kg | **HE28**: 28 seats, 1036 km range, $e_b$ = 500 Whr/kg |
| **FE48**: 48 seats, 1000 km range, $e_b$ = 700 Whr/kg | **HEA48**: 48 seats, 1000 km range, $e_b$ = 500 Whr/kg |
| | **HEB48**: 48 seats, 1302 km range, $e_b$ = 700 Whr/kg |
| | **HE70**: 70 seats, 1530 km range, $e_b$ = 700 Whr/kg |

In the methodology, other aircraft configurations for aircraft in the database are evaluated. Therefore, aircraft limitations for a maximum amount of seats should be taken into account. For the presented database, the maximum addition in seats is one row of seats for aircraft up to 48 seats and two rows of seats for larger aircraft. The number of rows can always decrease until no more seats are left.

Costs for electrified aircraft are based on the cost of kerosene aircraft. The cost values for aircraft *Q200* and *Q400* are translated to linear cost equations dependent on the number of seats. The resulting equations are presented in Table 6 and are used to give a cost estimation of the electrified aircraft.

Table 6: Cost formulation

| **Cost division** | **Relation to number of seats** |
|---|---:|
| Cost per aircraft per day | $2429 + 56.5 * \#seats$ |
| Cost per trip | $367 + 8.5 * \#seats$ |
| Cost per hour | $987 + 23.0 * \#seats$ |
| Cost per km | $0 + 0 * \#seats$ |

Next to the electrified aircraft design, the operations required for electrified aircraft should be determined. The electrified aircraft operation focuses on the charging operation. The electrified aircraft will be recharged by a battery swapping station. The required time for recharging and refueling is taken into account by the relative *reloading* times stated in Table 7. These values were introduced in section 1.2.

Table 7: Relative aircraft reloading times

| **Aircraft type** | **Reloading time** |
|---|---:|
| kerosene | 5 min |
| fully-electric | 10 min |
| hybrid-electric | 25 min |

With the relative *reloading* time, the turnaround time per aircraft technology type can be distinguished. The turnaround time including refueling for the kerosene fleet is set at 30 minutes, which shows a turnaround time excluding refueling equal to 25 minutes. Turnaround times including reloading for the different aircraft technologies will become, 30 minutes for kerosene aircraft, 35 minutes for fully-electric aircraft, and 50 minutes for hybrid-electric aircraft.

Furthermore, the charging locations should be defined in the network. To start with, the charging facilities will be located at the same airports as where refueling facilities are present. This results in a situation where recharging is not possible at every airport, and the network should be defined in routes instead of single flights.

To achieve this, routes are defined as presented in the Network and fleet model. Routes can consist of one or multiple subsequent flights, and start and end at an airport with a charging facility.

### 3.4 Model assumptions

To implement the airline network in the presented methodology, the following assumptions have been made.

- The objective is to maximize profit.
- The model is run for an average week, thus 7 days. The input consists of average weekly demand and average weekly PSO requirements. The demand includes demand for connecting flights.
- The PSO requirements for frequency and capacity have been taken into account.
- The load factor is assumed to be 0.85, thus future flights expect to be filled for 85%.
- The stop factor and transfer factor are assumed to be 1, thus stops and transfers do not impact the yield value.
- The maximum time an aircraft can be operated per day, the maximum block time, is set at 9.35 hours.
- The required runway of Q200 is decreased to 760m to be operated in CVU and the required runway of Q400 is decreased to 1340m to be operated in FLW. This can be assumed while the take-off weight is smaller than the maximum take-off weight.
- Kerosene price is €0.80 per kg.
- Battery energy is €0.1445 per kWh.
- For the aircraft configuration, the weight of one extra seat including passenger and baggage is 112 kg.
- The maximum route size is set at 4 airports, thus 3 subsequent flights. Larger route sizes lead to long computational times.
- A good estimation of the network and fleet is reached within 600 seconds, therefore the time limit for the optimization is set at this value.

## 4 Results

With the information presented in the previous sections, the methodology is executed. The interest is to study the adaptation of SATA Air Açores to fleet replacement by electrified aircraft. The effect on network development, network performance, and fleet choice can be compared with a reference situation, which is the current situation. In the reference situation, the fleet is given by the aircraft currently operated, the *Q200* and *Q400*. This reference situation can also serve as model validation and is presented in section 4.1.

Then in section 4.2, the methodology is performed with a fleet consisting of electrified aircraft. The choice for aircraft configuration and network is first presented for a fully-electric fleet and a hybrid-electric fleet independently. Thereafter, the results for a mixed fleet of fully- and hybrid-electric aircraft are presented. As it is likely in the future situation that kerosene aircraft are not replaced at one moment, the mixed situation of both electrified and kerosene aircraft is obtained as well.

The outcome consists of information regarding network performance, network development, and selected aircraft designs and configurations. A lot of information can thus be presented. The goal of this paper is to study how airlines can strategically adapt to the implementation of electrified aircraft and see the selected aircraft designs. Therefore, the choice has been made to focus on the airline performance in terms of profit and $CO_2$ emission, the difference in operating routes, and chosen aircraft designs.

The airline can not only adapt to electrified aircraft by changing its routes, frequencies, and fleet, but by changing network characteristics as well. Characteristics that can be influenced by the airline are fleet diversity, location of charging facilities, turnaround times, reloading times, and the maximum block time. The impact of changing these network characteristics on the adaptation is analyzed by scenarios in section 4.3.

Besides the airline choices, external factors can influence the adaptation. This could $CO_2$ taxes, fuel and battery energy prices, and costs of electrified aircraft. The impact of these factors on the airlines' adaptation is analyzed in scenarios in section 4.4.

To study the choice for aircraft design, the aircraft costs per aircraft type and per seat are presented in Table 12 in Appendix A.2. These cost values include the cost for fuel and energy consumption with the prices presented in the Model assumptions. Note that new aircraft configurations are included in the table.

## 4.1 Reference situation

The reference situation is implemented by selecting the current kerosene aircraft, the *Q200* and *Q400*, as available aircraft for the fleet. For this situation, the aircraft configurations are not variable, and thus the network and fleet model is executed without the extension for other configurations. A selection of the results is presented in Table 8. The number after the aircraft type presents the amount of aircraft chosen. More details, for example on the cost values and the number of passengers transported, are presented in Table 13, Appendix B.1.

Table 8: Result current fleet

| | **Profit (OF) [€]** | **$CO_2$ emission [kg]** | **Aircraft fleet** |
|---|---|---|---|
| **kerosene fleet** | $-94.0 * 10^4$ | $30.3 * 10^4$ | *Q200*(3), *Q400*(2) |

For this situation, the routes flown per aircraft type are visualized in Appendix B.2, Figure 10. Both aircraft operate on various distances, but the largest route distances are only operated by the *Q400*. The profit is given by a large negative value since the financial compensation of the PSO flights is not included. Therefore, also other situations and scenarios will result in negative profit values.

## 4.2 Situation with electrified aircraft

In this section, the methodology is performed with a fleet of electrified aircraft. Besides other available aircraft, the situation is not changed compared to the reference. First, the independent situations of a fully-electric fleet and a hybrid-electric fleet are presented.

When the methodology is performed for an exclusively fully-electric aircraft fleet, the results are presented in Table 9. By choosing a profitable new aircraft configuration each iteration, the objective function becomes higher throughout the iterations. In iteration 3, no other aircraft configurations are proposed and thus the final set of aircraft designs is reached. For the fully-electric aircraft fleet, configurations with an increased payload and decreased range are preferred. The largest aircraft design, the *FE48+1* is most dominantly chosen. Extensive results on the performance of the final iteration are given in Appendix B.1.

Table 9: Result fully-electric fleet

| | **IT** | **Profit (OF) [€]** | **$CO_2$ emission [kg]** | **Aircraft fleet** | **New aircraft** |
|---|---|---|---|---|---|
| **FE** | 0 | $-118.0 * 10^4$ | 0 | *FE28*(2), *FE48*(5) | *FE48+1* |
| **FE** | 1 | $-111.9 * 10^4$ | 0 | *FE20*(1), *FE28*(2), *FE48+1*(4) | *FE28+1* |
| **FE** | 2 | $-108.3 * 10^4$ | 0 | *FE20*(1), *FE28+1*(2), *FE48+1*(4) | *FE20+1* |
| **FE** | 3 | $-107.9 * 10^4$ | 0 | *FE20+1*(1), *FE28+1*(2), *FE48+1*(4) | *none* |

Throughout the iterations, the two *FE28* and five *FE48* aircraft are replaced by one *FE20+1*, two *FE28+1*, and four *FE48+1*. While the fleet size stays at 7 aircraft, the ownership cost (−5%) and operating cost (−7%) reduce. Slightly fewer passengers are transported (−1%).

This new situation of operating exclusively fully-electric aircraft leads to a reduction in profit (−15%) compared to the reference situation. The fleet of 5 kerosene aircraft is replaced by 7 fully-electric aircraft, which requires higher ownership costs (+16%). The minimum trip time for this network has increased (+15%) due to lower speed and increased reloading times. This causes a larger fleet and higher operational costs (+7%). Still, fewer passengers are transported (−9%) which induces a lower revenue (−10%). It should be noted that when operating exclusively fully-electric aircraft, the $CO_2$ emission equals zero.

Three different aircraft designs have been chosen. The *FE20+1* is chosen mainly on shorter routes and the *FE28+1* on longer routes. The *FE48+1* is chosen for various route distances. Most of the chosen routes match the chosen routes in the reference situation. However, the largest route flown is 762 km and thus smaller than the reference situation (−25%), while the average route length is around equal (+1%). The total available seat kilometers decreased (−12%).

In Table 10, the results are presented when the methodology is performed for an exclusively hybrid-electric aircraft fleet. Again each iteration, a profitable aircraft configuration is chosen and contributes to the objective function. No more aircraft configurations are proposed in the third iteration, and a final set of aircraft designs is reached. The final set of aircraft designs is presented by a combination of original and new aircraft configurations. Not one aircraft design dominates in this situation. Besides the objective function which increases over the iterations, the $CO_2$ emission decreased over the iterations. Extensive results on the performance of the final iteration are presented in Appendix B.1.

Table 10: Result hybrid-electric fleet

| | **IT** | **Profit (OF) [€]** | **$CO_2$ emission [kg]** | **Aircraft fleet** | **New aircraft** |
|---|---|---|---|---|---|
| **HE** | 0 | $-111.8 * 10^4$ | $11.2 * 10^4$ | *HE20*(1), *HE28*(1), *HEA48*(2), *HEB48*(1), *HE70*(1) | *HE70+1* |
| **HE** | 1 | $-110.2 * 10^4$ | $11.0 * 10^4$ | *HE20*(1), *HE28*(1), *HEA48*(2), *HEB48*(1), *HE70+1*(2) | *HE70+2* |
| **HE** | 2 | $-107.9 * 10^4$ | $10.9 * 10^4$ | *HE28*(3), *HEA48*(1), *HEB48*(1), *HE70+2*(2) | *HE28+1* |
| **HE** | 3 | $-106.3 * 10^4$ | $10.8 * 10^4$ | *HE20*(1), *HE28+1*(2), *HEA48*(1), *HEB48*(1), *HE70+2*(2) | *none* |

Throughout the iterations, one *HEA48* aircraft is replaced by a new configuration, and the *HE28+1* and two *HE70* aircraft are replaced by two *HE70+2* aircraft. This decreases both ownership (−3%) and operating cost (−4%). Furthermore, the emission decreases (−3%) while slightly more passengers are transported (+1%) compared to the initial hybrid-electric situation.

Compared to the reference situation, operating exclusively hybrid-electric aircraft leads to a smaller profit (−13%) and a decrease in $CO_2$ emission (−64%). For the fleet, 7 hybrid-electric aircraft are chosen which bring higher ownership costs (+25%). The operating costs are increased as well (+3%), which can be related to the increased minimal trip time due to higher reloading times and reduced speed. In this new situation, fewer passengers are transported (−10%) which results in less revenue (−11%).

Five different aircraft designs have been chosen. The *HE20* mainly operates on short routes and the *HEB48* on medium-sized routes. The other aircraft, the *HE28+1*, the *HEA48*, and the *HE70+2*, operate on various route distances. Again, most operated routes match the chosen routes in the reference situation. Also, the maximum route distance is similar to the reference situation. However, the total available seat kilometers are decreased (−13%).

The chosen aircraft configurations are collected and mixed situations are implemented into the airline network. First, all electrified aircraft are taken into account, followed by a mix of electrified and kerosene aircraft. In both situations, the new aircraft configurations selected for fully- and hybrid-electric aircraft are included and no new aircraft configurations are proposed to add to the aircraft database.

The results of these mixed situations are presented together with the exclusive situations in Figure 5. In this figure, the profit and $CO_2$ emission are presented per situation simultaneously with the chosen aircraft fleet. The labels present the fleet composition, where *FE* presents fully-electric aircraft, *HE* presents hybrid-electric aircraft and *KE* presents kerosene aircraft. More information on the performance per fleet composition is presented in Appendix B.1.

In the situation where all electrified aircraft are available (*FE+HE*), the profit is increased regarding the exclusively fully-(*FE*) or hybrid-electric (*HE*) situations. Compared to the reference (*KE*) situation, the profit is yet decreased (−6%) but the $CO_2$ emission is highly decreased as well (−81%). For the fleet, 6 aircraft are chosen which increases the ownership costs (+12%). Having a longer minimal trip time (+15%) leads to higher operating costs (+1%). The amount of passengers and the revenue is decreased (both −8%). The new fleet consists of a mix of hybrid- and fully-electric aircraft. Furthermore, the chosen routes are like the reference situation and have similar maximum and average distances. The total available seat kilometers are decreased (−11%).

When both electrified as kerosene aircraft are available for the network (*FE+HE+KE*), a mix of these aircraft technology types is chosen. Compared to the reference situation, the profit has increased (+1.4%) and the $CO_2$ emission is decreased (−49%). Since this situation is more profitable than the reference situation, the replaced aircraft are studied. Table 12 is used.

The smaller kerosene aircraft in the reference situation, three *Q200* aircraft, are replaced by two *FE20+1*, one *HE28+1*, and one *HEB48*. The *FE20+1* is an aircraft with a smaller capacity than the *Q200* and thus both ownership and operating costs per aircraft are lower. However, the costs per seat show higher ownership and operating costs than for the *Q200*. Therefore, the *FE20+1* aircraft is interesting for routes where a small

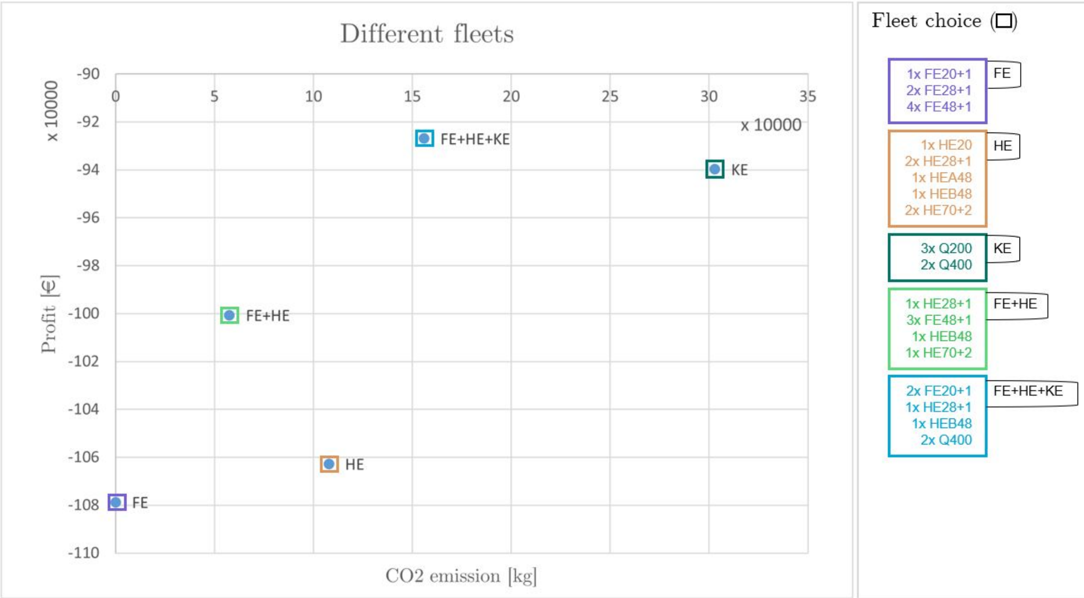



Figure 5: Performance with different fleets

capacity is required. Secondly, the *HE28+1* is chosen. When looking at the costs per seat, the ownership costs, costs per trip, and costs per hour are all somewhat higher than for the *Q200*, but the costs per kilometer are lower. Therefore, this aircraft is interesting to operate the longer distances that were previously flown by *Q200*. Thirdly, the *HEB48* is chosen. This aircraft has a larger capacity and is more expensive per aircraft than the *Q200*, but per seat, it has lower ownership and operating costs. Due to this, the aircraft is profitable to be operated on routes where a larger capacity is required. The operated routes in the *FE+HE+KE* situation are comparable with the reference situation. Per aircraft type, operated routes are presented in Appendix B.2, Figure 11.

For the fleet, now 6 aircraft are chosen instead of 5 in the reference case. This, together with the aircraft characteristics, leads to a situation with increased ownership costs (+9%), but a decrease in operational costs (−6%). Fewer passengers are transported (−9%) which leads to a decrease in revenue (−10%). The total available seat kilometers is decreased (−11%) as well.

### 4.3 Decisions of the airline

This section presents the impact of the airline on the adaptation of electrified aircraft. The airline has an impact on some network characteristics, namely the fleet diversity, location of charging facilities, turnaround times, reloading times, and maximum block times. The goal is to study the impact of varying these values on the adaptation of electrified aircraft. Since an adaptation is interesting when it is profitable for the airline, profitable network and fleet choices are studied for different scenarios. In previous results, minimal variation is obtained in the selected routes. Therefore, the focus is on the network performance and fleet choice. It should be taken into account that some changes require additional cost, but this is not elaborated upon. The reference situation in this section is the mixed situation with electrified and kerosene aircraft, presented in the previous section, and is labeled the *initial* situation.

Starting with the fleet diversity. In the mixed situation with electrified and kerosene aircraft, four different aircraft types are chosen to operate in the network. Regarding aircraft maintenance, it is beneficial for an airline to have less fleet diversity. Therefore, the impact of having a maximum fleet diversity is studied. Scenarios with a limit of 3, 2, and 1 different aircraft type(s) are studied and results are presented in Figure 6. Performance in profit and $CO_2$ emission per scenario can be obtained on the axes. Furthermore, the colored squares give information regarding the fleet choice. The initial situation, without a diversity limit, is presented in blue.

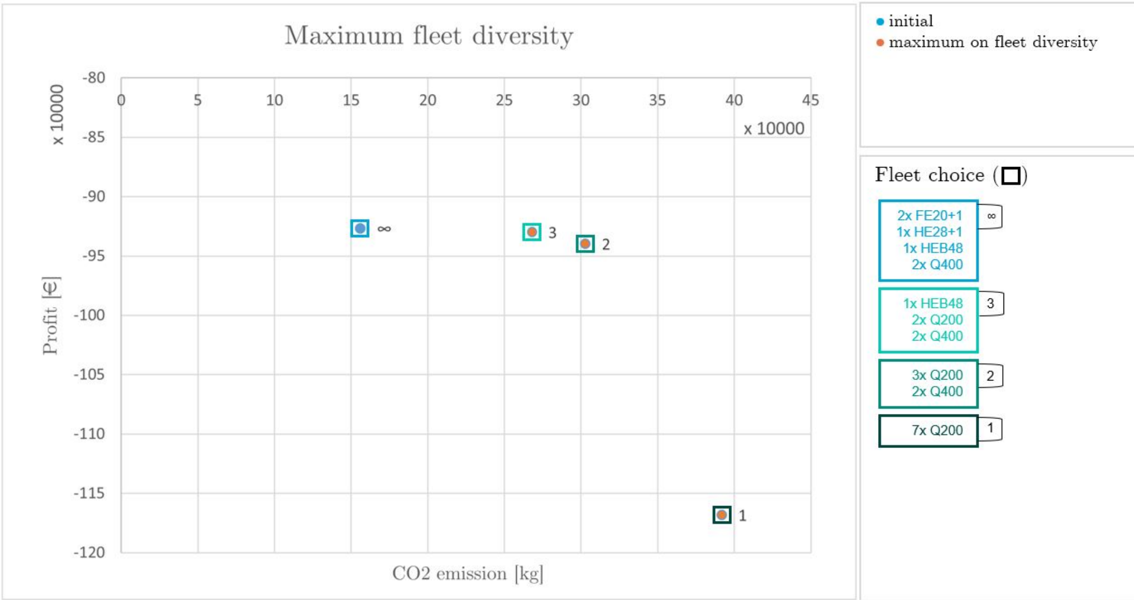



Figure 6: Performance with maximum fleet diversity

Minimizing the fleet diversity leads to the choice to operate less electrified aircraft, and thus makes the adaptation of electrified aircraft less attractive. The scenario with a maximum fleet diversity of two will even be most profitable with the current kerosene fleet.

Secondly, the choice of placement of charging facilities is analyzed. At this moment, refueling is possible at airports: PDL, TER, HOR, PIX, and SMA and it is assumed that charging facilities are located here as well. To see the impact of varying the amount of charging locations in the network, first the airports are arranged based on their demand sum. The order of airports in demand sum (from large to small) is PDL, TER, HOR, PIX, SJZ, SMA, FLW, GRW, and CVU. Scenarios with one up to nine charging locations are created, where charging is possible at the largest demand airports. So in the scenario with 5 charging locations, these are situated at PDL, TER, HOR, PIX, and SJZ. Note that this is different than the initial situation which also has 5 charging locations. Performance in profit and $CO_2$ emission per situation are presented in Figure 7 together with the performance of the initial situation. Labels present the amount of charging locations. To distinguish different scenarios, the choice is made to limit the axis to a smaller range. Therefore, the scenario with one charging location is not visible in the graph but is presented on the right. Besides the performance, the chosen fleet is presented as a colored square.

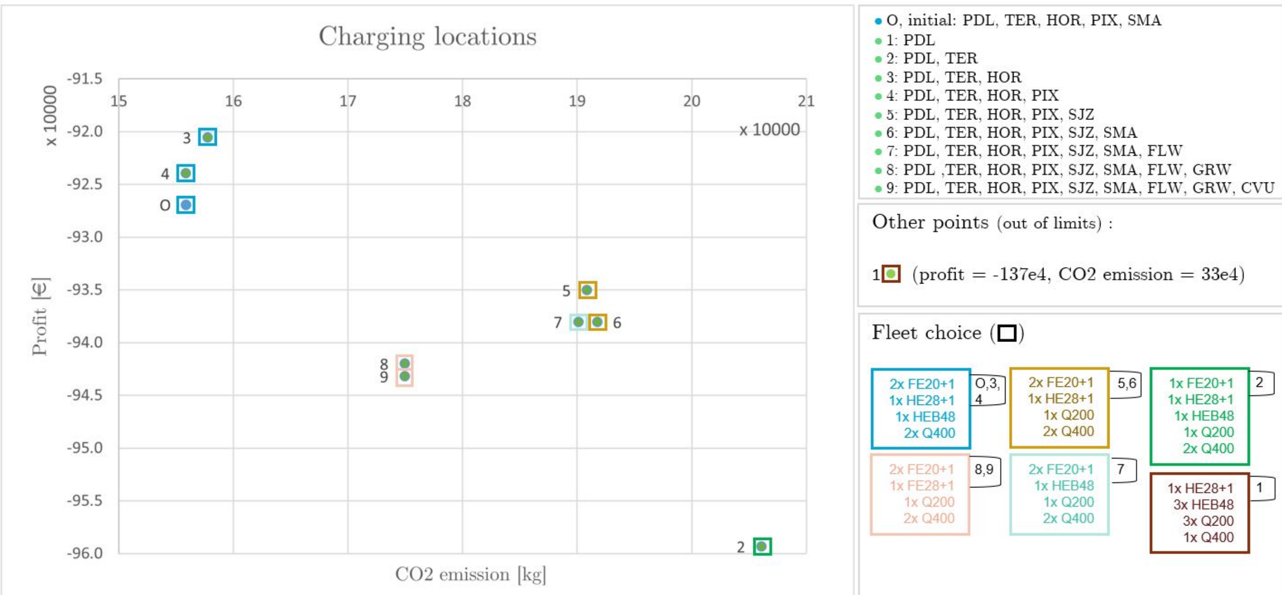



Figure 7: Performance with different charging locations

With 3 or 4 charging locations in the network, the network and fleet choice is similar to the initial situation. Both a lower and a higher amount of charging locations show the preference for operating a small kerosene aircraft, the *Q200*, instead of an electrified aircraft.

By interpreting these results, it should be noted that in this model the aircraft are recharged at every charging location. Therefore, having more charging locations requires more time and thus cost.

As third, the impact of changing time values in the network on the adaptation is studied. The values of the maximum block time, turnaround time, and reloading time are taken into account.

The maximum block time defines the number of hours an aircraft can be operated per day and equals 9.35 hours in the initial situation. To see the impact of the maximum block time on the adaptation, the block time is varied to 7,8,11, and 12 hours. The turnaround time without reloading in the initial situation is 25 minutes. To see the impact of speeding up or slowing down airport operations, a turnaround time is varied by 5 and 10 minutes up and down. The reloading time differs per aircraft technology type. The reloading time of electrified aircraft is quite higher than for kerosene aircraft. Therefore, the impact of speeding up the battery swap process by 10 minutes is interesting. Further, the impact of having equal reloading times for kerosene and electrified aircraft, thus all 5 minutes, is studied.

The proposed scenarios are implemented and results for adjusting operation times are visualized in Figure 8. Again the performance in profit and $CO_2$ emission is presented on the axes of the graph, and the fleet choice by the colored squares.

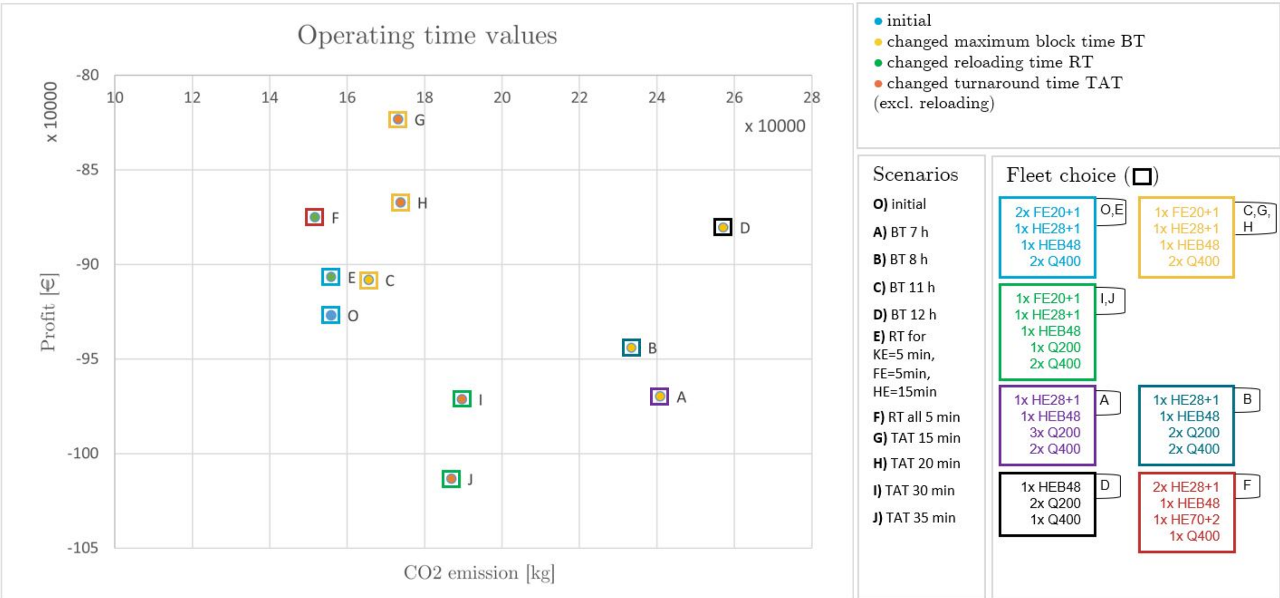



Figure 8: Performance with different operating times

When looking at the variation in maximum block time, the maximum block time impacts the fleet size. When having an increased maximum block time, fewer aircraft are operated in the fleet and electrified aircraft are absent compared to the initial situation. Decreasing the maximum block time causes more aircraft to be chosen in the fleet, with the choice of kerosene aircraft.

Decreasing reloading times for electrified aircraft by 10 minutes leads to more profit, but no other network and fleet choices. Setting all reloading times to 5 minutes causes a fleet replacement of one *Q400* by electrified aircraft. In this situation, only hybrid-electric aircraft are chosen beside one *Q400*.

Decreasing the turnaround time at the airport causes more profit and fewer aircraft in the fleet. Similar to increasing the block time, one electrified aircraft is missing compared to the initial situation. Increasing the turnaround time causes an electrified aircraft to be replaced by a *Q200*.

## 4.4 External factors

Additionally, external factors impact the adaptation of electrified aircraft. Cost values are dependent on the $CO_2$ tax, the pricing of kerosene and energy, and the costs of electrified aircraft. Similar to section 4.3, new scenarios are compared to the mixed situation of electrified and kerosene aircraft and the focus is on network performance and fleet choice.

In the initial situation, the $CO_2$ tax is zero. In the Problem context, a $CO_2$ tax of €0.041 per kg $CO_2$ is proposed. Scenarios are created with this value and multiplications of this value to see the impact on the adaptation. The initial kerosene price €0.80 per kg and the energy price €0.1445 per kWh. The impact of the kerosene and energy price is evaluated by scenarios with doubled or halved prices. The initial costs for electrified aircraft are similar to kerosene ones. Most likely, electrified aircraft will be more expensive. Based on the information in section 1.2, the costs of aircraft with a 500 Whr/kg battery are increased by 5%, 7.5%, and 10%, and of aircraft with a 700 Whr/kg battery simultaneously by 8.5%, 12.75%, and 17% to the initial situation. Results for all scenarios are presented in Figure 9. Performance in profit and $CO_2$ emission is presented in the axes of the graph, and the fleet choice by the colored squares.

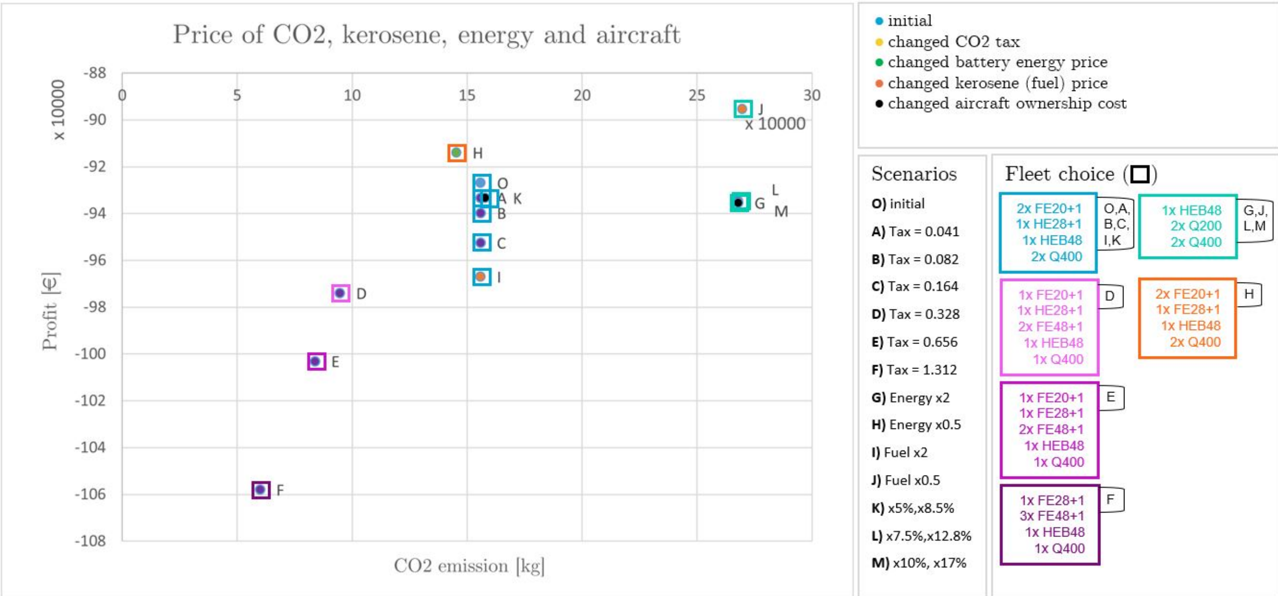



Figure 9: Performance with different $CO_2$ taxes, fuel and energy prices, and aircraft ownership costs

A $CO_2$ tax up to €0.164 per kg will not impact the network and fleet choices, only increased costs due to the tax occur. Higher values for $CO_2$ tax will present the choice for more fully-electric aircraft and a lower $CO_2$ emission. Doubling the energy price or halving the kerosene price leads to the choice for more kerosene aircraft and more $CO_2$ emission. On the other hand, halving the energy price or doubling the kerosene price does not have a large impact on the adaptation, besides the changed cost. Increasing the ownership costs for aircraft with a battery technology of 500 Whr/kg and 700 Whr/kg with 5% and 8.5% respectively has no large impact on the network and fleet choice. But increasing the by more than 7.5% and 12.8% respectively leads to the airlines' choice for operating more kerosene aircraft.

# 5 Conclusions

This research aims to study how airlines can strategically adapt to (the introduction of) electrified aircraft. Since the design of electrified aircraft is yet in a conceptual phase, a methodology is presented where strategic airline planning and electrified aircraft design are connected. In this methodology, new profitable aircraft configurations are found which give a positive contribution to the airline network. Results show that new aircraft configurations indeed contribute to the objective.

The methodology is performed on the airline network of SATA Air Açores, to study the airlines' adaptation to a proposed electrified fleet. With the objective to maximize profit, the network and fleet choices for different fleet types are presented in Table 5. Operating only electrified aircraft leads to a large reduction in $CO_2$ emission but a less profitable situation than the reference situation. However, operating a combination of electrified and kerosene aircraft leads to a more desirable network in terms of profit and $CO_2$ emission. Besides the network performance, it can be obtained that configurations with an increased capacity and a decreased range for electrified aircraft are preferred. In all situations, similar operating routes are selected. This is related to the fixed PSO requirements. With the new available aircraft types, the airline adapts by choosing aircraft types that can fulfill PSO requirements while the total available seat kilometers are decreased.

The influence of the airline on the adaptation of electrified aircraft is studied. For this, the situation with both electrified and kerosene aircraft is used. The airline can decide on fleet diversity, amount of charging locations, and operating time. When no limitation on the fleet diversity is set, a mix of electrified and kerosene aircraft is chosen. But by setting a limitation of 3, 2, or even only 1 aircraft type per fleet, the preference goes to kerosene aircraft. Therefore, allowing a fleet diversity of more than 2 would be stimulating for the adaptation of electrified aircraft. Further, the amount of charging locations can highly impact the preference for electrified aircraft. The airline can stimulate the adaptation of electrified aircraft by selecting specific charging locations. Third, the airline can adapt its operating times; such as maximum block time, reloading time, and turnaround time. From the analysis results that changing the maximum block time is not advantageous for the choice of electrified aircraft and the same holds for varying turnaround times. The network and fleet choice do change by changing these time values but to more kerosene aircraft instead of electrified aircraft. The reloading time is mainly important for the adaptation of hybrid-electric aircraft. When the reloading times for hybrid-electric aircraft are shortened to the reloading times of kerosene aircraft, choosing electrified aircraft is more attractive. Thus, for the adaptation of electrified aircraft by SATA Air Açores, focus on the fleet diversity, charging locations, and hybrid-electric reloading times rather than other operating times.

External factors that can impact the adaptation are the $CO_2$ tax, the price of fuel and energy, and electrified aircraft cost. For this airline, a $CO_2$ tax starting from €0.328 per kg will stimulate the adaptation of electrified aircraft compared to the situation without $CO_2$ tax. Regarding the pricing, lowering kerosene and increasing battery energy prices will lead to a preference for more kerosene aircraft. While lowering energy prices or increasing kerosene prices does not impact the choice for electrified aircraft. Further, the ownership costs of electrified aircraft can increase up to 5% and 8.5% for a battery-specific energy of 500 Whr/kg and 700 Whr/kg respectively without having much impact on the adaptation. Larger increments of ownership costs lead to the preference for kerosene aircraft. It is remarkable to see that a *HEB48* aircraft is chosen alongside kerosene aircraft in the fleet, while this aircraft has a high-level battery technology. Hence, for the adaptation of electrified aircraft, the choice for electrified aircraft can be stimulated by a large enough $CO_2$ tax but not by halving the energy price or doubling the kerosene price. The price of electrified aircraft can increase to a certain extent without having a large impact on the adaptation.

The adaptation of electrified aircraft is thus related to the current situation and decisions of the airline and external factors. However, for SATA Air Açores, the choice for network development is highly influenced by the PSO requirements set by the government and operating routes do not vary much when operating electrified aircraft. The choice for electrified aircraft designs shows a preference for a smaller fully-electric aircraft (*FE20+1*) in combination with a larger hybrid-electric aircraft (*HEB48*) and the largest kerosene aircraft (*Q400*). Looking at configurations, the option to have an increased passenger capacity and a decreased range is preferred. This can be related to small distances between the airports. In various scenarios, it is preferred to operate only the larger hybrid-electric aircraft besides the current fleet which makes this electrified aircraft design suitable for multiple airline scenarios.

# 6 Discussion and Recommendations

This section presents and discusses the limitations of this research and proposes recommendations for future research.

Starting with the limitations of this research. In the presented methodology, choices have been made that affect the research outcome.

The first to discuss is the model choice for the charging operation of electrified aircraft. In the network and fleet model, the aircraft is recharged in every route, and thus recharges every time the aircraft reaches an airport with a charging facility. If a route only consists of one flight, this means the aircraft is recharged after one flight, which might not be necessary. Charging the aircraft when this is not necessary will lead to redundant costs and operating time. However, this choice has been made since this is a strategic model, and no schedule is created. Therefore, the state of charge of the aircraft can not be obtained and it can not be included if an aircraft has to recharge for its next route.

Secondly, the choice of the aircraft design method. For this research is chosen to create initial electrified aircraft designs with the *Initiator*, and establish different configurations with the *Breguet Range equation.* For the initial set of aircraft, the seat versus range configuration can be modified, but no new exterior designs are considered. This limits the exterior design to the initial set given. Next to this, a limit exists for the configuration as well. Per iteration, the configuration can be adjusted by one row. Thereby, a maximum on the number of rows that can fit in the aircraft is set. Due to this, not all electrified aircraft sizes in terms of passenger capacity can be evaluated. Thus in this research, the aircraft design is limited to the initial aircraft database and constrained configuration options. When the research presents the final set of aircraft designs, it does not mean that there are no other profitable aircraft designs. However, it does mean that there are no profitable aircraft designs within the research possibilities.

The methodology is executed on SATA Air Açores. For this airline, some limitations occur as well.

Starting with the influence of the PSO regulation. In this network, none of the routes is profitable to be operated and thus the impact of PSO requirements on the chosen routes is high. Only flights that should be flown are flown and varying the airlines' fleet has little impact on the route choice. Therefore, this situation is not suitable to study the impact of operating electrified aircraft on the route choice.

Furthermore, the costs of the eight electrified aircraft presented in the initial aircraft database is highly uncertain. However, these cost values highly impact the network and fleet choice since the objective is to maximize profit.

Lastly, to reduce computational time, a maximum of possible routes is set to routes with a maximum of three successive flights. This limits the case study because the impact of a combination with larger route sizes can not be studied. Only the impact of having exclusively routes with four successive flights is obtained in a sensitivity analysis.

For future research, recommendations are resulting from this research.

Starting with the establishment of routes. In this research, all possible combinations of successive airports, starting and ending at a charging airport, are taken into account. For the case study, this resulted in high computational time. For future research, it is recommended to introduce a pre-selection of routes. With a pre-selection, unlogical routes can be eliminated, the number of routes will decrease and more route sizes can be included without exceeding computational limits.

Secondly, when evaluating the impact of decisions of the airline and external factors, cross effects are not included. As multiple aspects can change, it is recommended for future research to study the impact of changing multiple elements and their cross effects on the network and fleet choice.

Another recommendation for future research is a more extensive aircraft design method. In this research, the electrified aircraft design is limited to the initial aircraft database and constrained configuration options. The exterior of a given aircraft can not be adjusted. When it is possible to propose an aircraft type with linear expressions for size, total fuel and battery energy, fuel and battery energy consumption, and runway size dependent on the amount of seats, these expressions can give various exterior and interior aircraft designs. The linear expressions enable the aircraft design to be coupled with the network and fleet model. Like this, the electrified aircraft design is less limited and various aircraft sizes and configurations can be chosen. Therefore, for future research, it is recommended to find a way to present variable aircraft designs and their characteristics in linear expressions dependent on the number of seats. And to couple this design method with the presented network and fleet model.

Nevertheless, the cost estimation for operating electrified aircraft should receive attention. Since information on the ownership, operating, and charging costs is lacking, this research consists of estimations and it is recommended to investigate these cost values.

# References


[1] Pipistrel Aircraft. Pipistrel price configurator. URL `https://www.pipistrel-prices.com/configurator/configure/815/`.

[2] SATA Azores Airlines. Sata, 2021. URL `https://www.azoresairlines.pt/`.

[3] José Alexandre, T.G. Fregnani, Bento S. De Mattos, and José A. Hernandes. An innovative approach for integrated airline network and aircraft family optimization. *Chinese Journal of Aeronautics*, 33(2):634–663, 2020. ISSN 1000-9361. doi: https://doi.org/10.1016/j.cja.2019.10.004. URL `https://www.sciencedirect.com/science/article/pii/S1000936119304042`.

[4] Kevin R. Antcliff and Francisco M. Capristan. *Conceptual Design of the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) Concept.* doi: 10.2514/6.2017-4001. URL `sacd.larc.nasa.gov/wp-content/uploads/sites/102/2017/10/Antcliff_Aviation2017_PEGASUS.pdf`.

[5] Joseph Ausserer. *Integration, Testing, and Validation of a Small Hybrid-Electric Remotely-Piloted Aircraft.* PhD thesis, 03 2012.

[6] Peter Belobaba, Amedeo Odoni, and Cynthia Barnhart. *The Global Airline Industry.* John Wiley & Sons, 2009.

[7] Benjamin J. Brelje and Joaquim R.R.A. Martins. Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts, models, and design approaches. *Progress in Aerospace Sciences*, 104:1–19, 2019. ISSN 0376-0421. doi: https://doi.org/10.1016/j.paerosci.2018.06.004. URL `https://www.sciencedirect.com/science/article/pii/S0376042118300356`.

[8] Volvo Cars. Onze auto's, 2022. URL `www.volvocars.com/`.

[9] European Commission. the european green deal, 2020. URL `https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en`.

[10] William Crossley and Muharrem Mane. *System of Systems Inspired Aircraft Sizing Applied to Commercial Aircraft / Airline Problems*. 2005. doi: 10.2514/6.2005-7426.

[11] William Crossley, Muharrem Mane, and A Nusawardhana. *Variable Resource Allocation Using Multidisciplinary Optimization: Initial Investigations for System of Systems*. 2004. doi: 10.2514/6.2004-4605.

[12] Navindran Davendralingam and William Crossley. *Concurrent Aircraft Design and Airline Network Design Incorporating Passenger Demand Models*. 2009. doi: 10.2514/6.2009-6971.

[13] Mathias de Koning and Bruno F. Santos. Fleet planning under demand uncertainty: a reinforcement learning approach. 2021.

[14] Reynard de Vries, Maurice Hoogreef, and Roelof Vos. *Preliminary Sizing of a Hybrid-Electric Passenger Aircraft Featuring Over-the-Wing Distributed-Propulsion*. doi: 10.2514/6.2019-1811.

[15] Reynard de Vries, Maurice F. M. Hoogreef, and Roelof Vos. Range equation for hybrid-electric aircraft with constant power split. *Journal of Aircraft*, 57(3):552–557, 2020. doi: 10.2514/1.C035734. URL `https://doi.org/10.2514/1.C035734`.

[16] R Elmendorp and Gianfranco La Rocca. Comparative design sensitivity studies on box-wing airplanes. 09 2019.

[17] Antony Evans, Andreas Schafer, and Lynnette Dray. *Modelling Airline Network Routing and Scheduling under Airport Capacity Constraints*. 2008. doi: 10.2514/6.2008-8855.

[18] FAA. Section 4: Aircraft operating costs. *Benefit-Cost Analysis*, 2022.

[19] Yann Fefermann, Christophe Maury, Clélia Level, Khaled Zarati, Jean-Philippe Salanne, Clément Pornet, Bruno Thoraval, and Askin Isikveren. Hybrid-electric motive power systems for commuter transport applications. 09 2016.

[20] D. Felix Finger, Reynard de Vries, Roelof Vos, Carsten Braun, and Cees Bil. *A Comparison of Hybrid-Electric Aircraft Sizing Methods*. doi: 10.2514/6.2020-1006.

[21] C. Friedrich and P.A. Robertson. Hybrid-electric propulsion for aircraft. *Journal of Aircraft*, 52(1):176–189, 2015. doi: 10.2514/1.C032660. URL `https://doi.org/10.2514/1.C032660`.

[22] Carla Grobler, Philip J Wolfe, Kingshuk Dasadhikari, Irene C Dedoussi, Florian Allroggen, Raymond L Speth, Sebastian D Eastham, Akshat Agarwal, Mark D Staples, Jayant Sabnis, and Steven R H Barrett. Marginal climate and air quality costs of aviation emissions. *Environmental Research Letters*, 14(11): 114031, nov 2019. doi: 10.1088/1748-9326/ab4942. URL `https://doi.org/10.1088/1748-9326/ab4942`.

[23] Mirko Hornung, Askin Isikveren, Mara Cole, and Andreas Sizmann. Ce-liner - case study for emobility in air transportation. 08 2013. ISBN 978-1-62410-225-7. doi: 10.2514/6.2013-4302.

[24] John Hwang, Satadru Roy, Jason Kao, Joaquim R. R. A. Martins, and William A. Crossley. *Simultaneous aircraft allocation and mission optimization using a modular adjoint approach*. 2015. doi: 10.2514/6.2015-0900.

[25] John T. Hwang and Joaquim R. R. A. Martins. *Parallel allocation-mission optimization of a 128-route network*. 2015. doi: 10.2514/6.2015-2321.

[26] John T. Hwang and Joaquim R. R. A. Martins. Allocation-mission-design optimization of next-generation aircraft using a parallel computational framework. In *57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. American Institute of Aeronautics and Astronautics, Jan 2016. doi: 10.2514/6.2016-1662.

[27] ICAO. Environmental report 2016. 2016. URL https://www.icao.int/environmental-protection/Documents/ICAO%20Environmental%20Report%202016.pdf.

[28] Askin Isikveren, Sascha Kaiser, Clément Pornet, and Patrick Vratny. Pre-design strategies and sizing techniques for dual-energy aircraft. *Aircraft engineering and aerospace technology*, 86:525–542, 10 2014. doi: 10.1108/AEAT-08-2014-0122.

[29] Neil Yorke-Smith Izaak L. Geursen and Bruno F. Santos. Fleet planning under demand and fuel price uncertainty. 2021.

[30] Patrick Jaillet, Gao Song, and Gang Yu. Airline network design and hub location problems. *Location Science*, 4(3):195–212, 1996. ISSN 0966-8349. doi: https://doi.org/10.1016/S0966-8349(96)00016-2. URL https://www.sciencedirect.com/science/article/pii/S0966834996000162. Hub Location.

[31] Ralph Jansen, Cheryl Bowman, Amy Jankovsky, Rodger Dyson, and James Felder. *Overview of NASA Electrified Aircraft Propulsion (EAP) Research for Large Subsonic Transports*. doi: 10.2514/6.2017-4701. URL https://arc.aiaa.org/doi/abs/10.2514/6.2017-4701.

[32] Scott M. Jones, W. Haller, and M. Tong. An n+3 technology level reference propulsion system. 2017.

[33] Cedric Y. Justin, Alexia P. Payan, Simon I. Briceno, Brian J. German, and Dimitri N. Mavris. Power optimized battery swap and recharge strategies for electric aircraft operations. *Transportation Research Part C: Emerging Technologies*, 115:102605, 2020. ISSN 0968-090X. doi: https://doi.org/10.1016/j.trc.2020.02.027. URL https://www.sciencedirect.com/science/article/pii/S0968090X19310241.

[34] Hooi Ling Khoo and Lay Eng Teoh. An optimal aircraft fleet management decision model under uncertainty. *Journal of Advanced Transportation*, 48(7):798–820, 2014.

[35] Hooi Ling Khoo and Lay Eng Teoh. A bi-objective dynamic programming approach for airline green fleet planning. *Transportation Research Part D: Transport and Environment*, 33:166–185, 2014. ISSN 1361-9209. doi: https://doi.org/10.1016/j.trd.2014.06.003. URL https://www.sciencedirect.com/science/article/pii/S1361920914000686.

[36] Ovidiu Listes and Rommert Dekker. A scenario aggregation–based approach for determining a robust airline fleet composition for dynamic capacity allocation. *Transportation Science*, 39(3):367–382, 2005.

[37] Muharrem Mane, William A. Crossley, and Nusawardhana. System-of-systems inspired aircraft sizing and airline resource allocation via decomposition. *Journal of Aircraft*, 44(4):1222–1235, 2007. doi: 10.2514/1.26333.

[38] Engineering National Academies of Sciences and Medicine. *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions*. The National Academies Press, Washington, DC, 2016. ISBN 978-0-309-44096-7. doi: 10.17226/23490. URL https://www.nap.edu/catalog/23490/commercial-aircraft-propulsion-and-energy-systems-research-reducing-global-carbon.

[39] United Nations. The paris agreement, 2015. URL https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[40] Royal Netherlands Aerospace Centre (NLR) and SEO Amsterdam Economics. Destination 2050. URL https://www.destination2050.eu/.

[41] Nusawardhana Nusawardhana and William Crossley. *Concurrent Aircraft Design and Variable Resource Allocation in Large Scale Fleet Networks*. 2009. doi: 10.2514/6.2009-6977.

[42] Tae Hoon Oum, Anming Zhang, and Yimin Zhang. Optimal demand for operating lease of aircraft. *Transportation Research Part B: Methodological*, 34(1):17–29, 2000.

[43] Martijn GJ Repko and Bruno F Santos. Scenario tree airline fleet planning for demand uncertainty. *Journal of Air Transport Management*, 65:198–208, 2017.

[44] Jonathan M. Rheaume and Charles Lents. Energy storage for commercial hybrid electric aircraft. In *SAE 2016 Aerospace Systems and Technology Conference*. SAE International, sep 2016. doi: https://doi.org/10.4271/2016-01-2014. URL https://doi.org/10.4271/2016-01-2014.

[45] Carlo E.D. Riboldi, Lorenzo Trainelli, Federico Bigoni, Francesco Salucci, and Alberto Rolando. Switching to electric propulsion: Fleet and infrastructure sizing. 09 2019.

[46] Satadru Roy and William A. Crossley. *An EGO-like Optimization Framework for Simultaneous Aircraft Design and Airline Allocation.* 2016. doi: 10.2514/6.2016-1659.

[47] Satadru Roy, Kenneth Moore, John T. Hwang, Justin S. Gray, William A. Crossley, and Joaquim R. R. A. Martins. *A Mixed Integer Efficient Global Optimization Algorithm for the Simultaneous Aircraft Allocation-Mission-Design Problem.* 2017. doi: 10.2514/6.2017-1305.

[48] Constantijn A.A. Sa, Bruno F. Santos, and John-Paul B. Clarke. Portfolio-based airline fleet planning under stochastic demand. *Omega*, 97:102101, 2020. ISSN 0305-0483. doi: https://doi.org/10.1016/j.omega.2019.08.008. URL `https://www.sciencedirect.com/science/article/pii/S0305048318304833`.

[49] Francesco Salucci, Lorenzo Trainelli, Roberto Faranda, and Michela Longo. An optimization model for airport infrastructures in support to electric aircraft. In *2019 IEEE Milan PowerTech*, pages 1–5, 2019. doi: 10.1109/PTC.2019.8810713.

[50] Francesco Salucci, Lorenzo Trainelli, Carlo E. Riboldi, and Alberto L. Rolando. *Sizing of Airport Recharging Infrastructures in Support to a Hybrid-Electric Fleet.* 2021. doi: 10.2514/6.2021-1682.

[51] Francesco Salucci, Lorenzo Trainelli, Carlo E. Riboldi, and Alberto L. Rolando. *Optimal sizing and operation of airport infrastructures in support of electric-powered aviation.* 2021.

[52] Bruno Santos. Lecture 1: Introduction, planning framework and demand analysis, 2020.

[53] GJ Schick and JW Stroup. Experience with a multi-year fleet planning model. *Omega*, 9(4):389–396, 1981.

[54] Michael Schmidt, Annika Paul, Mara Cole, and Kay Olaf Ploetner. Challenges for ground operations arising from aircraft concepts using alternative energy. *Journal of Air Transport Management*, 56:107–117, 2016. ISSN 0969-6997. doi: https://doi.org/10.1016/j.jairtraman.2016.04.023. URL `https://www.sciencedirect.com/science/article/pii/S096969971630165X`. Growing airline networks -Selected papers from the 18th ATRS World Conference, Bordeaux, France, 2014.

[55] S. Stückl, J. Toor, and H. Lobentanzer. Voltair - the all electric propulsion concept platform - a vision for atmospheric friendly flight. 4:2737–2747, 01 2012.

[56] Knut Sandberg Eriksen Svein Bråthen. Regional aviation and the pso system – level of service and social efficiency. *Journal of Air Transport Management*, 69:248–256, 2018. ISSN 0969-6997. doi: https://doi.org/10.1016/j.jairtraman.2016.10.002.

[57] Christine Taylor and Olivier de Weck. *Integrated Transportation Network Design Optimization.* 2006. doi: 10.2514/6.2006-1912.

[58] Desmond Di Wang, D. Klabjan, and Sergey Shebalov. Attractiveness-based airline network models with embedded spill and recapture. *Journal of Airline and Airport Management*, 4:1–25, 2014.

[59] Jacopo Zamboni, Roelof Vos, Mathias Emeneth, and Alexander Schneegans. *A Method for the Conceptual Design of Hybrid Electric Aircraft.* doi: 10.2514/6.2019-1587.

[60] P.J. Zijlema. The netherlands: list of fuels and standard co2 emission factors version of january 2020. *Annual update of fuel list for the Netherlands*, 2020.

# Appendices

## A Supplementary information on the case study

### A.1 Initial electrified aircraft database

The required aircraft specifications for the network and fleet model are presented in Table 11.

Table 11: Specifications of initial aircraft database

| **name** | **seats** | **speed** [km/h] | **specific energy batt** [Whr/kg] | **max energy** [kWh] | **max fuel** [kg] | **energy per stop** [kWh] | **energy per km** [kWh] | **fuel per stop** [kg] | **fuel per km** [kg] | **runway** [m] | **range** [km] | **MTOM** [tons] | **L/D** [-] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **HE20** | 20 | 473 | 500 | 564 | 79 | 20 | 1.36 | 10 | 0.17 | 793 | 400 | 11 | 15 |
| **HE28** | 28 | 460 | 500 | 2069 | 274 | 99 | 1.90 | 24 | 0.24 | 760 | 1036 | 20 | 21 |
| **HEA48** | 48 | 460 | 500 | 2808 | 372 | 137 | 2.67 | 34 | 0.34 | 1333 | 1000 | 29 | 23 |
| **HEB48** | 48 | 460 | 700 | 5712 | 754 | 259 | 4.19 | 64 | 0.53 | 1107 | 1302 | 36 | 18 |
| **HE70** | 70 | 450 | 700 | 8967 | 1183 | 401 | 5.60 | 99 | 0.71 | 1333 | 1530 | 53 | 21 |
| **FE20** | 20 | 473 | 500 | 2431 | 0 | 283 | 5.37 | 0 | 0 | 793 | 400 | 23 | 14 |
| **FE28** | 28 | 460 | 700 | 10462 | 0 | 949 | 9.18 | 0 | 0 | 760 | 1036 | 47 | 17 |
| **FE48** | 48 | 460 | 700 | 8617 | 0 | 806 | 7.81 | 0 | 0 | 1333 | 1000 | 43 | 20 |
| **Q200** | 37 | 535 | - | 0 | 2270 | 0 | 0 | 137 | 1.16 | 760 | 1839 | 31 | 19 |
| **Q400** | 80 | 667 | - | 0 | 3336 | 0 | 0 | 168 | 1.20 | 1340 | 2656 | 45 | 15 |

## A.2 Aircraft costs including fuel and energy cost

The aircraft costs, including fuel and energy costs, are presented to interpret why aircraft are chosen. The fuel and energy costs are taken as presented in Model assumptions, a value of €0.80 per kg kerosene and €0.1445 per kWh. The consumption per kilometer and trip (landing and take-off cycle) is included in the cost values. The total costs are presented per aircraft type and per seat in Table 12. Note, that new aircraft configurations found in the results are already added.

Table 12: Aircraft costs including fuel and energy per aircraft and per seat

| | **cost per aircraft type [€]** | | | | **average cost per seat [€]** | | | |
|---|---|---|---|---|---|---|---|---|
| | **cost /day** | **cost /trip** | **cost /hour** | **cost /km** | **cost /day** | **cost /trip** | **cost /hour** | **cost /km** |
| **HE20** | 3207 | 1178 | 1247 | 0.33 | 160 | 59 | 62 | 0.017 |
| **HE28** | 3659 | 1269 | 1431 | 0.47 | 131 | 45 | 51 | 0.017 |
| **HE28+1** | 3659 | 1269 | 1431 | 0.47 | 114 | 40 | 45 | 0.015 |
| **HEA48** | 4789 | 1453 | 1890 | 0.66 | 100 | 30 | 39 | 0.014 |
| **HEB48** | 4789 | 1495 | 1890 | 1.03 | 100 | 31 | 39 | 0.021 |
| **HE70** | 6031 | 1731 | 2395 | 1.38 | 86 | 25 | 34 | 0.020 |
| **HE70+1** | 6031 | 1731 | 2395 | 1.38 | 82 | 23 | 32 | 0.019 |
| **HE70+2** | 6031 | 1731 | 2395 | 1.38 | 77 | 22 | 31 | 0.018 |
| **FE20** | 3207 | 1208 | 1247 | 0.78 | 160 | 60 | 62 | 0.039 |
| **FE20+1** | 3207 | 1208 | 1247 | 0.78 | 146 | 55 | 57 | 0.035 |
| **FE28** | 3659 | 1372 | 1431 | 1.33 | 131 | 49 | 51 | 0.047 |
| **FE28+1** | 3659 | 1372 | 1431 | 1.33 | 114 | 43 | 45 | 0.041 |
| **FE48** | 4789 | 1522 | 1890 | 1.13 | 100 | 32 | 39 | 0.024 |
| **FE48+1** | 4789 | 1522 | 1890 | 1.13 | 92 | 29 | 36 | 0.022 |
| **Q200** | 4167 | 1422 | 1638 | 0.93 | 113 | 38 | 44 | 0.025 |
| **Q400** | 6596 | 1814 | 2625 | 0.96 | 82 | 23 | 33 | 0.012 |

# B Extensive results

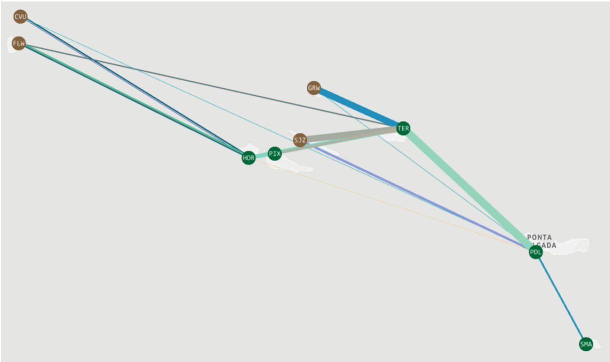
## B.1 Performance results with different fleets

Table 13: Performance results with different fleets

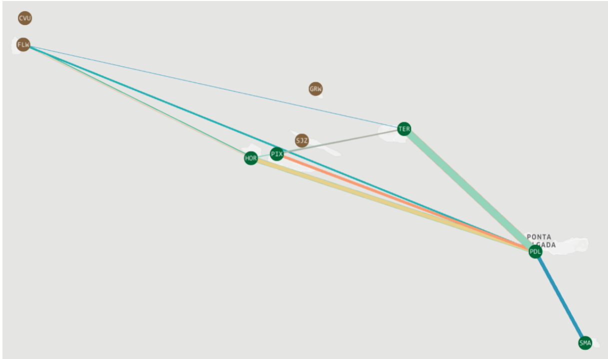
| input | profit [*10^4 €] | total ownership cost [*10^4 €] | total operating cost [*10^4 €] | total revenue [*10^4 €] | total passengers (transfer) [-] | average load factor [-] | total energy [kWh] | total fuel [kg] | total $CO_2$ emission [*10^4 kg] | total $CO_2$ cost [*10^4 €] | aircraft fleet |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **kerosene** | -94.0 | 18.0 | 113.5 | 37.5 | 11201 (801) | 0.80 | 0 | 97383 | 30.3 | 0 | 3x Q200<br>2x Q400 |
| **fully-electric** | -107.9 | 20.8 | 121.1 | 34.0 | 10212 (548) | 0.83 | 694239 | 0 | 0 | 0 | 1x FE20+1<br>2x FE28+1<br>4x FE48+1 |
| **hybrid-electric** | -106.3 | 22.5 | 117.2 | 33.4 | 10045 (532) | 0.83 | 219670 | 34679 | 10.8 | 0 | 1x HE20<br>2x HE28+1<br>1x HEA48<br>1x HEB48<br>2x HE70+2 |
| **all electrified** | -100.1 | 20.2 | 114.3 | 34.4 | 10344 (578) | 0.81 | 412337 | 18497 | 5.8 | 0 | 1x HE28+1<br>3x FE48+1<br>1x HEB48<br>1x HE70+2 |
| **electrified + kerosene** | -92.7 | 19.6 | 107.0 | 33.9 | 10180 (534) | 0.83 | 139316 | 50119 | 15.6 | 0 | 2x FE20+1<br>1x HE28+1<br>1x HEB48<br>2x Q400 |

## B.2 Visualization of routes per aircraft type

For the reference situation, chosen routes to operate per aircraft type are visualized in Figure 10. The colors represent the routes and the stroke size will correspond with the frequency on that route. Both aircraft operate on various distances, but the largest route distances are only operated by the *Q400*.



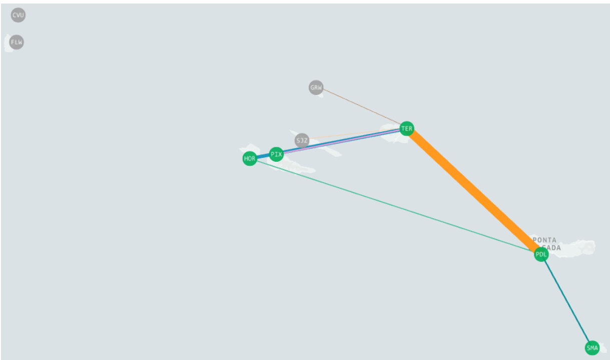
(a) Q200 (3 ac, max freq=17, avg. dist=222km, max dist=762 km)



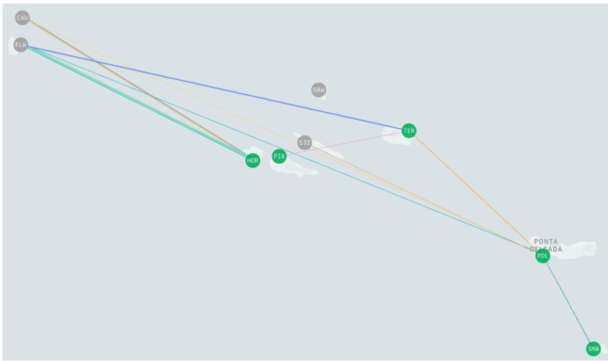
(b) HE28+1 (2 ac, max freq=17, avg. dist=229km, max dist=1020 km)

Figure 10: The developed network for the reference situation (kerosene aircraft)

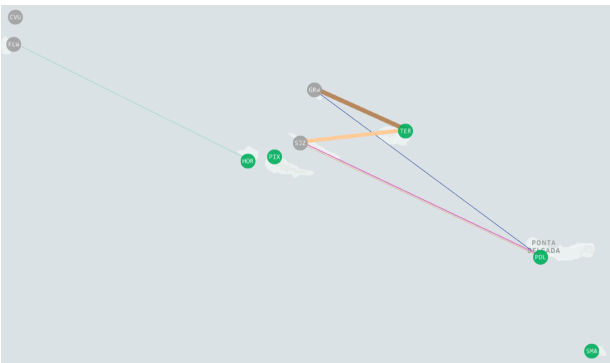
For the mixed situation with electrified and kerosene aircraft, chosen routes to operate per aircraft type are visualized in Figure 11. The colors again represent the routes and the stroke size will correspond with the frequency on that route. The routes flown by the *Q400* are similar to the reference situation. The routes flown by the *Q200* in the reference situation are now distributed over the *FE20+1*, the *HE28+1*, and the *Q400*.



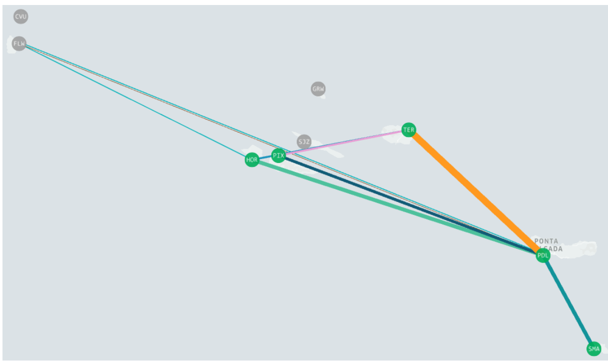
(a) FE20+1 (2 ac, max freq=18, avg. dist=158km, max dist=278 km)



(b) HE28+1 (1 ac, max freq=5, avg. dist=464km, max dist=762 km)



(c) HEB48 (1 ac, max freq=9, avg. dist=243km, max dist=480 km)



(d) Q400 (2 ac, max freq=14, avg. dist=213km, max dist=1020 km)

Figure 11: The developed network for a situation with fully-electric, hybrid-electric, and kerosene aircraft

# II

## Literature Study
previously graded under AE4020

.

# Electrified operations for regional airlines

## Impact of electrified operations on network and aircraft fleet development

**Literature study**

by

**Noa Zuijderwijk**

October 2021

Faculty of Aerospace Engineering,
University of Technology, Delft

| | | |
|---|---|---|
| Student number: | 4462343 | |
| Thesis committee: | Dr. ir. B.F. (Bruno) Lopes Dos Santos | TU Delft, supervisor |
| | Dr. ir. M.F.M. (Maurice) Hoogreef | TU Delft, supervisor |

# Contents

# Introduction

Worldwide, efforts to reduce the climate change are in progress [1]. As the air transport is responsible for around 2% of the $CO_2$ emission in 2018 and is still expanding (disregarding the Covid pandemic impact) [2], it is important to give attention to new measures that diminish the air transport share.

In order to reduce the environmental impact of air transport, different concepts have been created. The Destination 2050 report [3], presented by Europe's airlines, airports, aerospace manufacturers and air navigation service providers, proposes four areas of environmental development. The first is focused on improvements in aircraft and engine technologies, the second on sustainable aviation fuels, the third on smart economic measures and the fourth on improvements in air traffic management and aircraft operations. Within this work, the first area is targeted. Improvements in aircraft and engine technologies and subsequent fleet replacement should reduce the contribution of aviation to climate change. This could again be done in different ways. First of all the current propulsion systems can be made more fuel efficient. Secondly, hydrogen powered aircraft have potential to reduce the aircraft emissions. As third, aircraft driven by electrical energy will have less impact on climate change as fuel consumption and therefore emissions caused by fuel are reduced. The focus of this work is on the third option, and will present the introduction of electrified aircraft in the aviation industry. New aircraft technologies flying on fully-electric or hybrid-electric propulsion will replace the current airline fleet.

In order to switch to electrified aircraft, the airline network and the aircraft designs should be aligned. The development of electrified aircraft is starting at small aircraft designs and slowly expanding to larger ones [4] as the battery technology improves. To implement electrified aircraft as soon as possible, first the airline industry using smaller aircraft and ranges, thus regional airlines, will get attention. This work will concentrate on the regional airline network in Europe. This literature study will provide an overview of the current state-of-the-art in airline planning, the regional airline network in Europe and electrified aircraft designs with corresponding operations. The goal of the literature study is to find a way to combine electrified aircraft design with airline network development.

Background information on the airline planning process and the regional airline network in Europe is exposed in the first chapter, Background. Then the impact of incorporating electrified aircraft for an airline is evaluated in the second chapter, Electrified Operations. In order to see the current state-of-the-art models in airline fleet and network planning, the development of the optimization models have been elaborated upon in chapter 3, Planning models. Eventually, the important findings and gaps in literature will be discussed in the Conclusion.

# 1

# BACKGROUND

## 1.1. THE PLANNING FRAMEWORK

This section provides an overview of the airline planning process and highlights the focus of this project. A planning framework is presented in Figure 1.1. In this figure, different steps within the process are shown together with their time horizon on the left and the decision type on the right. The blue circle highlights the focus of this report, the long-term strategic airline decisions. Additional information to this section can be found in the book of Belobaba, Odoni, and Barnhart [5].

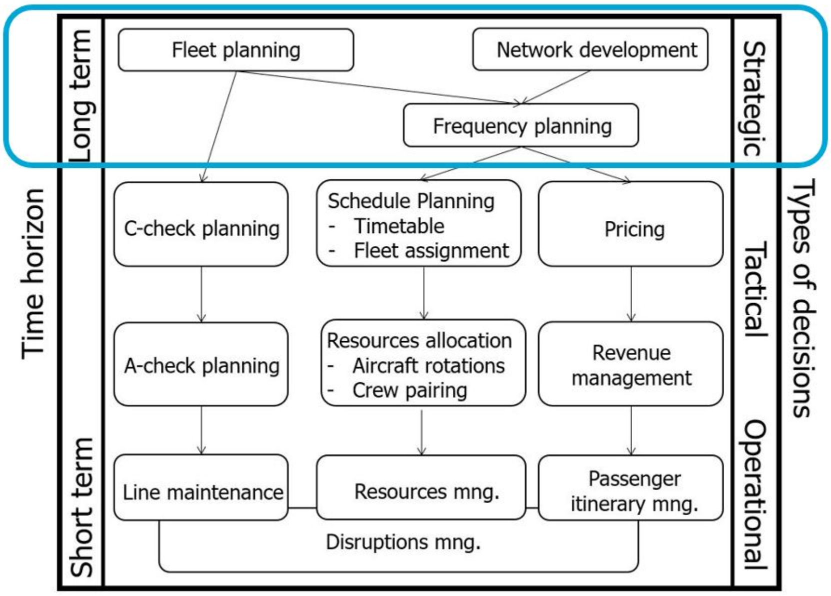



Figure 1.1: The Planning Framework [6]

The first outlined planning phase is the fleet planning [5]. In this long-term strategic phase an optimization of the future fleet is done. The objective of this phase is usually to optimize the airline's financial position by making decisions on when to retire existing aircraft or acquire new aircraft. The decisions include the timing to acquire and retire together with the amount and type of aircraft. When a new aircraft is planned for the fleet, this could take 10-15 years before the aircraft is actually present, therefore these types of decisions belong to the long term strategic decisions. The fleet planning is based on future demand, the revenue per seat or per flight and the fleet costs. Two different approaches can be used: the "top-down" or "macro" approach, or the "bottom-up" or "micro" approach. The "top-down" approach is based on relatively high-level aggregate analysis, where aggregate demand and cost data is used to evaluate financial impacts of the aircraft for a subsystem, region or route. This approach allows for a rapid evaluation of new aircraft types. The "bottom-up" approach is based on a much more detailed analysis of data and forecasts in the specific route network. Detailed models are used to produce the demand, operating cost, revenue, schedule and competitive characteristics which impact the fleet planning. As the approach takes much more details into account, the output is more detailed but also requires more effort of input and computational power. In practice, high uncertainty in future competition, demand and other conditions lead the future to remain highly speculative, and the simpler "top-down" approach is more commonly used. Relevant fleet planning models will be discussed in Section 3.1, Fleet planning.

Next to fleet planning, network development [5] is another long-term strategic planning phase. Network development is also called network planning or route planning, but should not be confused with aircraft-routing which is part of the tactical planning. In the network development phase, the specific routes to be flown by an airline are determined. Routes are evaluated by their profitability and economic considerations, formed by demand and revenue forecasts and the available airline fleet. An important consideration within network development is the choice for a hub, which distincts two network types: a Point-to-Point (PTP) network and a Hub-and-Spoke (H&S) network. Within a PTP network, all airports could be connected to each other, offering direct flights from place to place. Within a H&S network, one or multiple locations are chosen as a hub which are connected to all or several spoke airports. When this hub is not the origin or destination of the travel, the airport is used as a connecting stop between two flights in the passengers itineraries. H&S networks allow for feasible routes to cities with a small demand. In both networks, the routes will be chosen by their profitability. Like fleet planning models: demand, operating cost and revenue forecast give the input for the network consideration. Again, competitive effects are hard to implement. Relevant network development models will be discussed in Section 3.2, Network planning.

The last planning phase highlighted in the Planning Framework, is the frequency planning [5]. Within the frequency planning phase is determined how often the airline should operate flights on the selected route(s). In this book, the frequency planning is stated as a part of the schedule development, and thus more as a tactical planning phase. Throughout literature is obtained that frequency planning is often combined with network planning in order to determine the routes to fly, and therefore this planning phase is highlighted as well. The frequency planning is based on the aircraft fleet, available routes in the network and the demand per route. Frequency planning gives an indication of the flight schedule without determining exact departure, arrival and on-ground times. Within this planning phase can also be evaluated whether it is more profitable to fly a smaller aircraft multiple times per period, which is more convenient for the passenger as multiple departure times are available, or have a larger aircraft flying once per period, which results in lower cost per seat kilometer on the route. Consequently, the frequency planning is highly related to the fleet choice of the airline as well.

## 1.2. REGIONAL AIRLINE NETWORK EUROPE

Within the scope of this work, the regional airlines of Europe are considered. Regional airlines have arisen to connect airports with a smaller demand to larger airports that cooperate with legacy airlines. In this way, demand from small airports can be connected to the larger airline network.

At this moment, around forty regional airlines are present in Europe. The goal and network of these airlines can highly differ. For example, KLM Cityhopper is operating in a H&S network which reaches to cities throughout whole Europe while Sylt Air only connects the island Sylt with Hamburg, Germany. This difference can be explained by the function of regional airlines. When regional airlines are introduced to connect airports to the larger airline networks, they form a network with the aim to connect airline networks rather than to have an own independent airline network. In this section the regional airlines of Europe have been arranged on their network topology and aim. The categories are: small networks with only a few routes, medium size networks with routes mainly within the country, large networks that serve multiple countries and very large networks that serve almost every country in Europe.

Small regional airlines provide a connection between a few airports to a larger airport. These airlines can connect one or more islands to the mainland such as Sylt Air (Germany), Helvetic Airways (Switzerland) and Skybus to Isles of Scilly (UK) or provide a connection from smaller cities to larger ones within the country such as People's (Austria), Eagle Air (Iceland), Norlandair (Iceland) and AeroBratsk (Russia). Another small regional airline is SATA Air Açores (Portugal), which provides a connection between islands in Azoren and Madeira. Illustrations of these different airlines are presented in Figure 1.2.

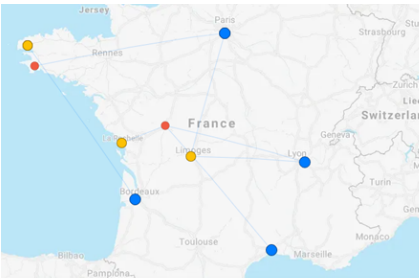

(a) Sylt Air, Germany [7]

(b) Eagle Air, Iceland [7]

(c) SATA Air Açores, Portugal [7]

Figure 1.2: Small regional airlines Europe

Medium size regional airlines fly within the country and occasionally to a city in a neighbouring country. As the goal of the airline is to connect to larger airline networks, the network topology of this regional airline could be quite free, such as Chalair and TwinJet (France). But the network could also be more structured and focused on one main airport, in this case the regional airline network will form as a H&S network. Examples of these medium size airlines are: Nordic Regional Airlines (Finland), Polar Airlines (Russia), Braathens Regional Airlines (Sweden), Aurigny Air Services (UK) and Blue Islands (UK). Most of the connections within the network are with one or multiple hub-airports, but also connection between the spoke-airports occur. When the airline aims to connect these airports to each other rather than to a larger hub-airport, the airline network will move to a PTP network. European examples of regional airlines with this network type are Air France Hop (France), Widerøe (Norway) and Loganair (UK). Connections between cities, but not all cities, are offered. Different airlines networks are visualized in Figure 1.3.



(a) Chalair, France [7]

(b) Braathens Regional Airlines, Sweden [7]

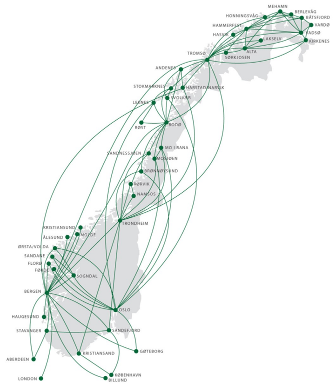
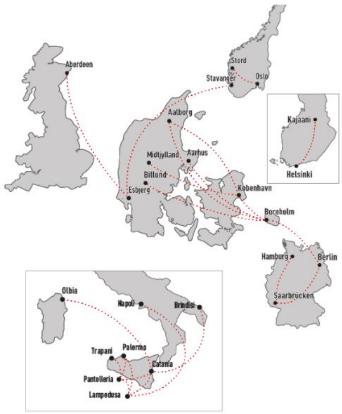
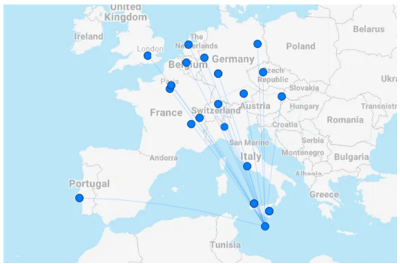

(c) Widerøe, Norway [8]

Figure 1.3: Medium size regional airlines Europe

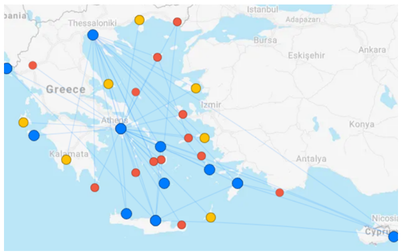
Large regional airlines serve multiple countries in Europe. The same type of networks as within the medium size regional airlines can be distinguished. First of all, some airlines operate various, not always connecting, routes, such as Danish Air Transport (Denmark). Single routes between two airports are served together with multiple routes to one larger airport. More structure is gained when the network is focused on one or more hubs, as in a H&S network, examples of airlines types having this network connecting multiple countries are Sun Air of Scandinavia (Denmark), Air Lingus Regional (Ireland), Alitalia Cityliner (Italy), Air Malta (Malta), TAP Express (Portugal), Carpatair (Romania) and Binter Canarias (Spain). Within these airline networks, one or more hubs are clearly visible.

Some large airlines have a network which is a mix of a H&S and PTP network. Here, "hubs" can be distinguished, but also connections between "spokes". Examples of airlines with this mixed network are: Olympic Air (Greece), SkyExpress (Greece), Air Dolomiti (Italy), Severstal Air Company (Russia) and Eastern Airways (UK). Again, a visualisation of these airline networks is given in Figure 1.4.





(b) Air Malta, Malta [7]



(c) Olympic Air, Greece [7]

(a) Danish Air Transport, Denmark [9]

Figure 1.4: Large regional airlines Europe

Lastly, even larger airlines can be differentiated. These regional airlines serve almost every country in Europe. These airlines are Lufthansa Cityline (Germany), CityJet (Ireland), KLM Cityhopper (Netherlands) and Air Nostrum (Spain). All these airlines have a hub in their own country and fly other European countries with a H&S network. Note that these regional airlines operate quite independent of larger (non regional) airlines. The network of Air Nostrum is shown in Figure 1.5.


Figure 1.5: Air Nostrum, Spain [10]

## 1.3. SUMMARY

The planning framework presents various steps in the airline planning process. Within this project, the focus is on the long term strategic planning decisions: fleet planning and network development. In the fleet planning phase, the acquisition and retirement planning of the aircraft fleet is determined with the goal to optimize the airline's financial position. For these models, a chosen network is used and the aircraft fleet is determined. To see a desirable network development, network planning models are also part of the strategic planning of airlines. Here profitable routes and network structure for the airline will be detected. In these models, the airlines aircraft fleet is known and the network is determined. In order to adjust both network and fleet together, not one of these planning phases can be used, but both should be studied and eventually in a way, be integrated.

Furthermore, the regional airline network in Europe is analyzed. Regional airlines have arisen to connect locations with smaller demand to the network of larger airlines. The regional airlines can be subdivided based on their network size. Various operating ranges and objectives can be distinguished between the airlines. In order to implement electrified aircraft, the performance of these aircraft should be aligned with the size, ranges and goals of the airline network type.

# 2

# Electrified Operations

In this chapter, the conditions of operating electrified aircraft are discussed. First of all, the state of the art of electrified aircraft is presented and discussed. Then the adaptations to the current airport infrastructure in order to operate electrified aircraft and the impact on airline operations is reviewed.

## 2.1. Electrified aircraft

In order to integrate electrified aircraft operations into airline planning, the current state-of-the-art of electrified aircraft designs should be analyzed. Within the electrified aircraft designs, a distinction is made between fully-electric and hybrid-electric aircraft designs, which will be discussed separately. Fully-electric aircraft are also called 'pure-electric' or 'universally-electric' aircraft [11]. Within the scope of this project, the aircraft have a commercial purpose to transport passengers.

Since 2000, various manned, electrified, fixed-wing aircraft have flown. The maximum capacity realized so far is 4 seats [11]. To operate regional flights, an increased capacity is required. This larger capacity, ranging from 10 to 100 seats, is at this moment only reached in concept studies. Therefore, this section will provide an overview of the different electrified aircraft design concepts with a minimum amount of four seats. To start with, some of the aircraft characteristics will be explained, such as the specific energy, the specific power and the degree-of-hybridization. Then state-of-the-art concepts will be presented including these characteristics.

The feasibility of the aircraft concepts is highly related to the specific energy and specific power of the aircraft system. The specific energy refers to the energy per mass of energy storage in the batteries and the specific power to the power of a component per unit mass in electric motors, power conversion electronics an energy storage devices. Therefore, the specific energy is related to the level of battery technology and the specific energy to the aircraft propulsion system. The flying range is directly proportional to the specific energy of the aircraft [11]. As batteries nowadays have an order 50 times lower specific energy than liquid fuels, the design for both electrified aircraft and batteries is challenging [12]. At this moment, the penalty of carrying heavy batteries is larger than the total energy advantage gained for long-range missions [11]. The currently realized specific energy of an aircraft reaches to 207 Whr/kg for the Airbus E-Fan [13]. Note that the specific energy is often referred to as the specific energy at pack level rather than cell level. The NAE, National Academy of Engineering, expects the specific energy to reach 400-600 Whr/kg at pack level by 2035 [14] and NASA predicts a future battery technology that can deliver 400-1000 Whr/kg at pack level [12] [15]. Besides the specific battery energy, the specific power of the batteries can be a constraint in the design. Some parts in the flight envelope can require significantly more power. The battery should be able to release this power in a short amount of time. Unfortunately, specific power trades off with specific energy [16]. Next to the specific energy and specific power of the aircraft, the efficiency of its electrical components has an impact on the feasibility as well. However, the efficiency has a smaller impact on the flying range [11] and therefor the focus is on the specific energy and power within this study. More information about the efficiency of components and constraints is provided by Pornet *et al.* [17].

Classifications occur within the electrified aircraft designs. This classification is based on the degree-of-hybridization of the aircraft. The degree is determined by the hybridization with respect to the specific electric motor power: $H_p$ and with respect to the specific battery energy: $H_e$ of the aircraft.[18] [19]. The degrees of hybridization are given for a conventional aircraft, a hybrid-electric aircraft and a fully-electric aircraft in Table 2.1. Different distinctions can be made within hybrid-electric aircraft. In this study, a distinction is made in 3 categories, but this could be even more detailed. The first one is a turboelectric aircraft, which uses combustible fuel in order to produce (and store) energy. Thus no energy is available without fuel and the produced energy is used to drive the propulsors. Turboelectric designs can be identified as simply hybrids without batteries [11]. A schematic illustration of the turboelectric propulsion is visible as a part of the serial architecture in Figure 2.1b [20].

Table 2.1: Degree of hybridization

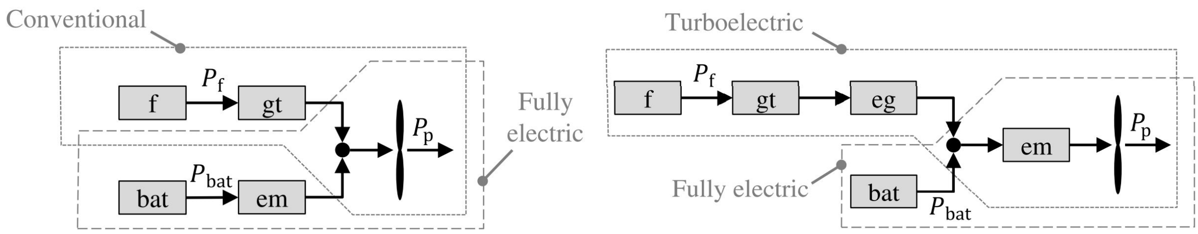
| **aircraft type** | **subtype** | **$H_p$** | **$H_e$** |
|---|---|---|---|
| conventional | | 0 | 0 |
| fully-electric | | 1 | 1 |
| hybrid-electric | | >0 | <1 |
| | turboelectric | >0 | 0 |
| | parallel hybrid | <1 | $0<H_e<1$ |
| | serial hybrid | 1 | $0<H_e<1$ |

The other hybrid-electric aircraft designs are formed by combining the architectures mentioned above. A parallel hybrid architecture is a conventional and fully electric propulsion combined, the power is delivered both by a gas turbine or thermal engine powered by fuel and by an electrical motor powered by batteries. The exact contribution of each power supply can differ. A schematic representation is given in Figure 2.1a [20].

Another architecture is a serial hybrid architecture, which is a turboelectric design combined with a fully-electric one. The energy for the electrical motor is supplied by energy from the batteries together with the energy from the gas turbine or thermal engine powered by fuel. The exact contribution of each power supply can again differ. A schematic representation is given in Figure 2.1b [20]. A general form of a hybrid architecture can thus be given by a combination of power supply by fuel and batteries, given in Figure 2.2 [20].

Consequently, the state-of-the-art concepts will be presented first for fully-electric aircraft, followed by the hybrid-electric aircraft including the turboelectric aircraft.

To compare the performance of the aircraft designs and their feasibility, for every aircraft design the same performance indicators are presented. These indicators are the capacity in seats, the peak power (MW), the required battery energy (Whr/kg), the maximum takeoff weight MTOM (kg) and the range (h or nmi). When a value is unknown, no value is given. It can be noted that aircraft costs are not specified, this choice has been made since this information is not yet available for these electrified aircraft.




(a) Parallel architecture

(b) Serial architecture

Figure 2.1: Hybrid architectures [20]

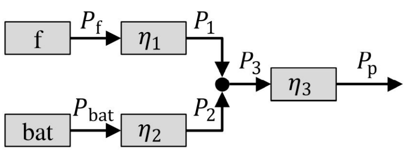



Figure 2.2: General hybrid architecture [20]

## FULLY-ELECTRIC AIRCRAFT DESIGNS

So far, several fully-electric aircraft designs are executed in reality, such as the Lange Antares, the Fisherman Electraflyer, Yuneec, Pipistrel Taurus Electro, IFB Stuttgart eGenius, Chip Yates Long ESA and the Airbus E-Fan [11]. Throughout these designs, only the Pipistrel Taurus Electro G4 reached a capacity of 4 passengers. As an electric aircraft for the purpose of regional transport is required, conceptual designs are analyzed where capacity rises to more than 4 seats .

For the following aircraft designs, specifications have been given in Table 2.2. Starting with aircraft designs of Eviation and Ampaire, which both have 9 seats. Eviation made a design consisting two wingtip-mounted pusher propellors and a tailcone propellor with some boundary-layer ingestion [11] [21]. Ampaire designed the Tailwind aircraft which is still in its conceptual phase. A concept featuring an aft boundary layer ingestion propulsor, similar to the STARC-ABL discussed later, is used and the desired range would go to 100 miles [22].

A larger aircraft design is the Airbus VoltAir. This aircraft design is part of an Airbus-funded study for an all-electric regional airliner. This design is interesting for regional transportation as the capacity is around 33 seats. Unfortunately, this design is only presented in a conference paper by Stückl *et al.* [23] and not elaborated afterwards. Furthermore, the required battery energy of more than 750 Whr/kg is not (yet) realistic.

The largest fully-electric aircraft designs are the Ce-Liner and Wright Electric. The Ce-Liner is designed by Bauhaus Luftfahrt and has 189 seats. The aircraft uses a C-wing shape for high aerodynamic efficiency and HTS electronics [24]. In order to fly, the aircraft requires a battery energy of 2000 Whr/kg which is extremely high compared with the available battery energy now. NASA with partnership of EasyJet designed the Wright Electric aircraft design, this aircraft owns 186 seats. The aircraft has distributed motors and high aspect ratio wings, but is still much in a concept phase and no more specifications are given [25].

Next to the aircraft concept designs, studies to the sizing of electric aircraft has been done. Finger, de Vries, Vos, Braun, and Bil [26] looked at two methods in order to size a 19 passenger aircraft. A parallel-hybrid, serial-hybrid and fully-electric aircraft have been evaluated. The sizing of the fully-electric aircraft is added in Table 2.2. This design is called "beyond optimistic" regarding the specific power and specific energy of the battery. Larger ranges (> 690 nmi) are not achievable with this fully-electric design, since a larger range will require more batteries which will lead to a MTOM above 50 tons, which is infeasible for a 19-seat aircraft.

Table 2.2: Fully-electric aircraft design concepts

| Aircraft | Manufacturer | Seats | peak power [MW] | battery energy [Whr/kg] | MTOM [kg] | Range [h] or [nmi] |
|---|---|---|---|---|---|---|
| Alice | Eviation | 9 | 2*0.64 | | 7484 | 440 nmi |
| Tailwind | Ampaire | 9 | | | | 87 nmi |
| VoltAir | Airbus | ~33 | | 750+ | ~33000 | ~900 nmi |
| Wright Electric | NASA and EasyJet | 186 | 2 | | | 695 nmi |
| Ce-Liner | Bauhaus Luftfahrt | 189 | 33.5 | 2000 | 109300 | 900 nmi |
| concept design | Finger *et al.* [26] | 19 | 6 kW/kg | 1500 | 81700 | 214 nmi |

### HYBRID-ELECTRIC AIRCRAFT DESIGNS

When looking at the hybrid-electric aircraft designs, realized aircraft are: the Siemens /Diamond E-Star, the Embry-Riddle Eco-Eagle, the Cambridge SOUL and the Airbus E-Fan 1.2 [11]. These realized aircraft have a maximum capacity of 2 seats and are therefore not suited for regional transportation. Consequently, aircraft designs with a larger capacity will be discussed. An overview of discussed aircraft design concepts and their characteristics are given in Table 2.3.

One of the smaller hybrid-electric aircraft designs is the XTI Tri-Fan 600. Due to three ducted fans in the wings this aircraft can fly in horizontal and vertical direction and suits as a VTOL (vertical takeoff and landing) vehicle. Battery technologies should evolve in order to realize this aircraft [27]. A slightly larger hybrid-electric aircraft is the Zunum Aero funded by Boeing and JetBlue and is suitable for regional operations. The design has integrated batteries in the wing and the series hybrid powertrain has an eventual transition to full electric [28].

The UNIFIER19 has 19 seats and is designed in collaboration of Pipistrel, Politechnico Milano and TU Delft. As the project is still ungoing, not much information about the performance is yet revealed. It aims to provide a near-zero emission aircraft [29]. Another 19-seats aircraft is the Eco Otter SX of Ampaire, which is a low-emission variant of the regional Twin Otter turboprob. The aircraft design can transport either 19 passengers or 4000+ lbs cargo [30].

An hybrid-electric commuter aircraft, named PACIFYC, is designed with a tri-prop approach (two on-wing padded turbo-props and one aft-fuselage mounted electric motor configured as a pusher-on-pylon installation) for operations with a maximum range of 700nmi [31]. This aircraft design is further used by Rossi [32] in order to make a procedure to design all-electric or serial hybrid-electric aircraft. Another aircraft design evaluated in the thesis of Rossi is a large regional aircraft. This aircraft is based on an ATR 72-600 and has a turboshaft generator and a high-performance Li-S battery. The aircraft is not yet feasible as the amount of battery energy required is not yet available.

One more aircraft designed for regional transport is the PEGASUS, Parallel Electric-Gas Architecture with Synergistic Utilization Scheme. This concept is a hybrid-electric regional aircraft and uses parallel hybrid-electric propulsors at the wingtips [33].

Larger regional hybrid-electric aircraft designs are presented by Airbus: the E-Fan X and E-Thrust. The E-Fan X is a design in cooperation with Rolls Royce and aims for a capacity from 50 to 100 seats. The project has been ended in 2020, and no more performance metrics are available [34]. The E-Thrust is an aircraft concept designed in 2013 by Airbus and could reach a capacity of 90 seats and serves for regional transport. To the writers knowledge, no more research is done with this aircraft concept and performance indicators are not further specified.

At last, an outstanding aircraft design in terms of passenger capacity is presented for hybrid-electric operations: the SUGAR Volt designed by Boeing. Boeing designed different SUGAR (Subsonic Ultra-Green Aircraft) concepts and only the SUGAR Volt was able to meet the NASA's N+3 fuel burn goal [35]. The aircraft design contains 154 seats and would be able to fly 3500 nmi. With a required battery energy of 750Whr/kg, this aircraft is not (yet) feasible.

In addition to the aircraft design concepts mentioned above, different people have been studying the sizing of hybrid-electric aircraft. The specifications are given in Table 2.4. Zamboni, Vos, Emeneth, and Schneegans [36] has sized a parallel, hybrid and series hybrid aircraft. The assumption for the cell specific energy is set at 750 Wh/kg, which they think is very optimistic since this could only be achievable with technologies such as lithium-air. Hoogreef, Vos, de Vries, and Veldhuis [37] looked at an aircraft with boosted turbofan (parallel-hybrid), a distributed leading-edge propulsion (DLEP) aircraft (serial-hybrid) and an over-the-wing distributed propulsion with propulsive empennage (ODPwPE) aircraft. The aircraft designs are compared with the A320 Novair and all have the same specific power and battery energy. The battery power is 2 kW/kg and

Table 2.3: Hybrid-electric aircraft design concepts

| **Aircraft** | **Manufacturer** | **Hybrid type** | **Seats** | **peak power [MW]** | **battery energy [Whr/kg]** | **MTOM [kg]** | **Range [h] or [nmi]** |
|---|---|---|---|---|---|---|---|
| Tri-Fan 600 | XTI | serial | 6 | 1.5 | | 2404 | 1200 nmi |
| Zunum Aero | Boeing and JetBlue | serial | 12 | 1 | | 5216 | 700 nmi |
| UNIFIER19 | Pipistrel, TU Delft, Politechnico Milano | serial | 19 | | | | |
| Eco Otter SX | Ampaire | parallel | 19 | 1 | | | 174+ nmi |
| PACIFYC | Fefermann *et al.* [31] | | 19 | 1.1 | 500 | | 700 nmi |
| Pegasus | NASA | parallel | 48 | | 500 | | 200-400 nmi |
| Large regional | Rossi [32] | serial | 70 | | 2000-5000 | | 700 nmi |
| E-Fan X | Airbus and Rolls Royce | serial | 50-100 | 4X2 | | | |
| E-Thrust | Airbus | serial | 90 | 9 | 1000 | | |
| SUGAR Volt | Boeing | parallel | 154 | | 750 | 68040 | 3500 nmi |

the battery energy is 500 Whr/kg at pack level. de Vries, Hoogreef, and Vos [38] did a sizing of a hybrid version of the ATR72-600 which is series/parallel partial hybrid. The battery energy and battery power are optimistic but not beyond realistic. As introduced earlier, Finger, de Vries, Vos, Braun, and Bil [26] compared different sizing methods. Also parallel- and serial-hybrid designs have been analysed. A 19-seat aircraft has been sized based on the different ranges. As the range increases, the battery size and weight increases and the available payload reduces which lead to less passengers which can be transported. For the serial-hybrid concept, the range of 1275 nmi is unfeasible due to the weight of the powertrain. Note that these designs are called "beyond optimistic" using a specific power of 6 kW/kg and a battery energy of 1500 Whr/kg.

*Turboelectric aircraft designs*

Besides the series and parallel hybrid-electric aircraft designs, turboelectric aircraft are upcoming in the hybrid-electric design concepts. To the writers knowledge, turboelectric aircraft are not yet brought to reality and only conceptual designs exist. The three main designs within this propulsion technology are the ECO-150R, the STARC-ABL and N3-X, shown in Table 2.5. The ECO-150R is designed by the aerospace corporation ESAero and is a single-aisle hybrid electric airplane for commercial transport. It has a series turboelectric architecture with 16 electric fans embedded in the wing. The STARC-ABL, Single-aisle Turboelectric AirCRaft – Aft Boundary Layer, is designed by NASA. The aircraft design has a conventional single aisle tube-and-wing configuration and uses boundary layer ingestion.[39] The N3-X is designed by NASA and is the largest designed concept so far, and designed with the Boeing 777 characteristics of seats and range: the aircraft is able to seat 300 passengers and has a range of 7500 nmi [40]. As a turboelectric aircraft does not require batteries, the required battery energy does not apply.

Table 2.4: Hybrid-electric aircraft sizing concepts

| Aircraft | Author | Architecture | Seats | peak power [MW] | battery energy [Whr/kg] | MTOM [kg] | Range [h] or [nmi] |
|---|---|---|---|---|---|---|---|
| concept design ATR72-600 | Zamboni *et al.* [36] | parallel | 70 | 1.7 | 750 | 25600 | 1530 nmi |
| concept design ATR72-600 | Zamboni *et al.* [36] | hybrid | 70 | 2.6 | 750 | 28500 | 1530 nmi |
| concept design ATR72-600 | Zamboni *et al.* [36] | series | 70 | 3.2 | 750 | 28800 | 1530 nmi |
| concept design Boosted Turbofan | Hoogreef *et al.* [37] | parallel | 180 | 39.8 | 500 | 57900 | >800 nmi |
| concept design DLEP | Hoogreef *et al.* [37] | serial | 180 | 28.3 | 500 | 86400 | >800 nmi |
| concept design ODPwPE | Hoogreef *et al.* [37] | serial | 180 | 46.0 | 500 | 93900 | >800 nmi |
| concept design ATR72-600 | de Vries *et al.* [38] | SPPH series/parallel partial hybrid | 70 | 1 kW/kg | 500 | 24100 | 825 nmi |
| concept design | Finger *et al.* [26] | parallel | 19 | 6 kW/kg | 1500 | 6360 | 214 nmi |
| concept design | Finger *et al.* [26] | parallel | 13 | 6 kW/kg | 1500 | 7060 | 691 nmi |
| concept design | Finger *et al.* [26] | parallel | 5 | 6 kW/kg | 1500 | 13470 | 1275 nmi |
| concept design | Finger *et al.* [26] | serial | 19 | 6 kW/kg | 1500 | 8300 | 214 nmi |
| concept design | Finger *et al.* [26] | serial | 13 | 6 kW/kg | 1500 | 12520 | 961 nmi |

Table 2.5: Turboelectric aircraft design concepts

| Aircraft | Manufacturer | Seats | peak power [MW] | battery energy [Whr/kg] | MTOM [kg] | Range [h] or [nmi] |
|---|---|---|---|---|---|---|
| ECO-150R | ESAero | 150 | 0.780 | - | 60-75k | 1650 nmi |
| STARC-ABL | NASA | 154 | 2.6 | - | 60k | 3500 nmi |
| N3-X | NASA | 300 | 50 | - | 227k | 7500 nmi |

In order to integrate the electrified aircraft to air transportation and select adequate designs, the industry needs to look out for suitable regulation and certification standards [41]. As these are not yet specified for electrified aircraft, the implementation of these aircraft in reality is more difficult. Within Europe, the European Union Aviation Safety Agency (EASA) is responsible for these adjustments.

## 2.2. AIRPORT INFRASTRUCTURE

In this section, the required airport infrastructure in order to operate electrified aircraft is presented. The analysis of the literature will focus on the differences to current airport operations and infrastructure and the impact on airline operations.

Within the airline operations, the airport infrastructure determines the turnaround time of an aircraft. The turnaround time is the time between the arrival of an aircraft at parking position and departure from that position. In regular operations this turnaround time includes disembarking, boarding, cleaning, refueling and the exchange of catering, bulk cargo, cargo containers, waste water and potable water. Within electrified airport operations, this turnaround time will also include recharging the aircraft. Besides, in the case of a fully-electric aircraft, there is no refueling time.

In order to charge electrified aircraft, two methods can be used [42]. The first one is a Battery Recharging Stations (BRS), where the batteries are charged similar to refuelling fuel in the aircraft. This method is commonly used in electric cars. The other method is a Battery Swapping Station (BSS), here the empty battery is removed from the aircraft and is replaced by a full one. For BSS, additional batteries and storage capacity is required to fulfil the operations. An advantage of this method is that one location can be used to charge the batteries and this location can be controlled in terms of temperature and energy grid loading. This is an important advantage as the temperature of batteries influences the battery condition and therefore the degradation and maintenance cost [43]. However, when making a choice between these two methods, the major decision maker nowadays is charging time. With the BRS method, the turnaround time of the aircraft highly depends on the charging time. Current chargers have the charging capacity of around 200kW, and in the future this is expected to be around 400kW and perhaps 800kW [44]. Note that the most promising vehicle charger design at this moment is the one of Porsche, with 450kW [45]. A regional aircraft, based on the hybrid-electric versions of the DH8D, ATR42 and ATR72, needs between 1000 and 1400 kWh [44]. This means that with the current capacity, the recharging takes around 6 hours, with 400kW chargers around 3 hours and with 800kW chargers around 1.5 hours. A hybrid-electric version of the B737-800, thus around 215 seats, even requires between 3500 and 7000kWh [46] and requires a way longer charging time. Therefore, with current technology, the charging times are too long to make the BRS method realistic. Research into the airport operations for electrified aircraft therefore only focus on the BSS method, or a combination of BRS and BSS [42] [47] [48] [49].

As said previously, the focus of this section is on the impact for airline operations. The airport infrastructure has effect on the airline operations in terms of turnaround time and costs. Regarding the previous section and available literature, focus is on the BSS method. For this method, the changing turnaround time will be presented.

Schmidt, Paul, Cole, and Ploetner [50] presented the turnaround times for two new aircraft types compared to the A320-2035. The A320-2035 is a future concept of the A320 – 2012 considered new technology levels. The two new aircraft designs with a comparable amount of seats are: the SUGAR Volt, a hybrid-electric aircraft, and the Ce-liner, a fully-electric aircraft, which are both introduced in the previous section: Electrified aircraft. Both aircraft make use of battery packages to provide energy which can be swapped to recharge. In order to estimate the turnaround times of these aircraft the time required for the different processes is determined. The refueling will take place when there are no passengers inside the aircraft, as do the processes inside the aircraft cabin such as cleaning and catering.

For the A320-2035 the turnaround lasts 41 minutes based on a full service turn around process with 180 passengers at gate position. The critical path for the turnaround time is the passenger disembarking, refueling and passenger boarding.
For the electrified aircraft concepts some assumptions have been made. First, the battery exchange and refueling of the aircraft can happen at the same time. Secondly, the battery exchange is allowed with passengers onboard (unlike the refueling).

The operations of a SUGAR Volt will require special equipment to swap the battery packages. The refueling time will decrease due to the reduced amount of fuel needed for the flight. As the battery exchange can take place while passengers are in the aircraft and there is a reduction of 15% in number of passengers, the total turnaround time for the SUGAR Volt is estimated at 34 minutes. The critical path within this time is given by the passenger disembarking, cleaning/refuelling and passenger boarding.

The Ce-Liner will operate fully electric and thus need no refueling. As the hybrid concept, this aircraft need special equipment in order to replace the (even heavier) battery packs. With a passenger increase of 5%, the turnaround time of the Ce-Liner will be 34 minutes as well. The critical path is the battery/cargo container loading for this aircraft. If the number of cargo containers can be highly reduced, the turnaround time could decline to 28 minutes.

Due to safety argumentation, the battery exchange while passengers are on board could be prohibited in the future. This will have an impact on the turnaround times of the aircraft concepts. The turnaround time of the SUGAR Volt will increase to 58 minutes (+71%) and the turnaround time of the Ce-liner to 48 minutes (+41%).

## 2.3. SUMMARY

In this chapter, the conditions of operating electrified aircraft have been discussed. Starting with the state-of-the-art of electrified aircraft and then going over the required infrastructure for electrified operations.

In order to present the current state-of-the-art of electrified aircraft designs, the designs have been filtered for suitability for regional transport. The minimum amount of seats for the presented concepts is four. Furthermore, the aircraft designs have been classified in two groups, the fully-electric and hybrid-electric aircraft designs. Within the hybrid-electric aircraft designs a distinction between turboelectric, serial hybrid-electric and parallel hybrid-electric can be made based on their degree-of-hybridization. Conceptual aircraft designs are presented for these different groups and a major point of discussion is the feasibility of the aircraft designs.

The feasibility of the design is highly related to the specific battery energy and peak power required. The current realized specific energy of an aircraft reaches to 207 Whr/kg for the Airbus E-Fan [13]. For the future: NAE expects the specific energy to reach 400-600 Whr/kg at pack level by 2035 [14] and NASA predicts a future battery technology that can deliver 400-1000 Whr/kg at pack level [12][15]. Conceptual aircraft designs often have a required specific energy of 500-750 Whr/kg, which is stated optimistic but possibly feasible for the future. Moreover, aircraft designs with a required battery energy of 2000 Whr/kg at pack level are presented, but this feasibility should be questioned.

When analyzing these electrified aircraft, note that in the turboelectric aircraft designs still fuel is used to produce energy and fly the aircraft. Batteries replace a part of the fuel in serial-hybrid or parallel-hybrid architecture or completely in a fully-electric architecture. Within the aircraft designs which (partly) fly on batteries and suitable for regional airline operations (more than 4 seats), the fully-electric aircraft desire significantly more specific battery energy than hybrid-electric ones. As increasing the specific energy is already challenging, it is more likely for hybrid-electric aircraft to become feasible in the future than fully-electric aircraft.

Furthermore, for electrified aircraft, a trade-off occurs between amount of batteries (and thus energy), range and seats. When it is desired to increase the flying range of the aircraft, the amount of batteries needs to increase to provide the required energy. This increase in batteries raises the weight of the aircraft and to remain the same MTOW, less passengers can be transported. This works the other way around as well, when it is desired to transport more passengers either the battery capacity needs to increase, or the range decreases.

Thereafter, the impact of the required airport infrastructure for electrified operations on airline operations needs to be determined. When looking to the airline operations, the airport operations influence the turnaround time and the turnaround cost of the aircraft. In order to evaluate this impact, the method of charging is important. Charging can be done by a BRS which is similar to the current refuelling stations or by a BSS which swaps the empty batteries for charged ones. As the charging capacity of the BRS at this moment leads to too long charging times, this method is at this moment unfit for electrified airport operations. The BSS is therefore the only option feasible at this moment, and research in literature has been focused on this method or a combination of both methods.

Schmidt, Paul, Cole, and Ploetner [50] presented the turnaround times for two new aircraft types: the SUGAR Volt, a hybrid-electric aircraft, and the Ce-liner, a fully-electric aircraft. With a BSS and the allowance to swap batteries while passengers are on board, both turnaround times require 34 minutes. If the swapping can not take place when passengers are on board, this turnaround time rises to 58 minutes for the SUGAR Volt and 48 minutes for the Ce-liner. The reference aircraft is the A320-2035, a future concept of the A320-2012, and has a turnaround time of 41 minutes.

# 3

# PLANNING MODELS

The steps of the airline planning have been discussed in Section 1.1. For the long-term strategic planning of an airline, both fleet planning and network planning are presented. The goal of fleet planning is to determine the optimal aircraft (fleet) for the future within a given airline network. The goal of network planning (or development) is to determine the optimal routes to fly with an available fleet. Since in this project, both network and fleet composition are optimized, both planning phases are considered. In this chapter, models developed for these planning phases are presented and the evolution over years is given. First, the fleet planning models will be discussed followed by the network planning models. Subsequently, these planning phases are combined into network&fleet planning models and aircraft design is integrated in the planning.

## 3.1. FLEET PLANNING

The fleet planning is an important step in the airline planning process as it highly influences the airlines financial situation. Over the years, many models on fleet planning have been developed. In order to structure this literature search, a division is made between deterministic and stochastic models. Within the deterministic models, input values are assumed to be known, while in stochastic models the uncertainty of the future is included. Solution techniques will be presented afterwards.

### DETERMINISTIC MODELS

The first known fleet planning model was that of Dantzig and Fulkerson [51] (1954), where the number of tankers needed to meet a fixed schedule was minimized. This linear programming model is single-stage and hence independent of time. Regarding the size of the model, it could be solved by hand. As the interest to determine a strategic fleet size continued, Kirby [52] (1959) derived an expression to determine the right fleet size, where the cost of the vehicle are compared with its usage. In order to take a fluctuating or seasonal demand into account, Wyatt [53] (1961) provided a method in which transport cost are minimized including a periodic demand.

The first work to make a distinction between aircraft buying and leasing was Fetter [54](1961). A linear programming model was created to find the optimal mix of leasing and buying. The demand is modelled as number of transport units required. As there is no limitation on the addition of extra contracted units, the model can give an operationally infeasible solution. The models of Kirby [52] and Wyatt [53] were not suited for non-homogeneous fleets and therefore Gould [55](1969) build further upon these models to include a non-homogeneous fleet. This model is named the first model of the 'general fleet sizing problem'. The demand is presented as a frequency distribution.

The models of Kirby [52] and Wyatt [53] were used again by New [56](1975), who presented an application to the work of Fetter [54] and Gould [55]. In this multi-period linear model, budget restraints and policies to maintain an optimal fleet size over time are included. The acquisition and disposal of equipment in a transport fleet is planned with the goal to meet all expected demand while minimizing operational cost. Furthermore New [56] stated that non-integer solutions are acceptable in order to decrease complexity.

Another author which presented a non-homogeneous multi-stage fleet plan, was Shube and Stroup [57](1975). A fleet planning per year was created for a 10-year period where cost are minimized. This linear programming model takes into account among other things: required service frequencies, traffic growth rates and existing fleet choices inspired by two schedule planning models of Etschmaier [58](1973) and Simpson [59](1969). Subsequently, this model is used for application to real airline planning in the linear programming model of Schick and Stroup [60](1981). This model is known to present the added value of automation of computer (assisted) models compared to manual planning.

With the models presented above, a foundation of deterministic fleet planning models is build. The focus of airline planners is changing to stochastic models, presented next. Only a few relevant deterministic models are realised over the last years. One of these is the one of Sayarshad and Ghoseiri [61](2009); where the fleet sizing model is integrated with fleet allocation. Deterministic travel times are included in the optimization and all travel demand is fulfilled. Furthermore, Bazargan and Hartman [62](2012) showed a fleet planning model with a top-down approach and presented an extensive search to collect the relevant parameters. By analyzing historical data, the parameters are determined and used to create a binary-integer linear programming model to optimize fleet planning.

### STOCHASTIC MODELS

As models evolve, the desire to include uncertainty increases. This could be an uncertainty in demand, but also in aircraft or fuel pricing. Since the beginning of a new era, the focus in fleet planning is on stochastic modelling.

One of the first stochastic models is the two-stage stochastic model of Oum, Zhang, and Zhang [63](2000). In this model the optimal purchasing and leasing policy to account for fluctuations and uncertainties in demand is presented where a distinction can be made between short and long-term leases. In this model the fleet mix characteristics are not comprehended. A following two-stage fleet planning model is of Listes and

Dekker [64](2002), where a scenario aggregation based approach is used. The goal is to design a strategic support tool for determining a fleet composition flexible enough for the successful implementation of the dynamic capacity allocation concept; where the assignment of aircraft to the flight schedule is done shortly before the actual operation in order to better match demand and available capacity in cases of high variability in demand. The second stage includes a fleet assignment model. A shortcoming is that multi periodicity is not included. Some years later, Listes and Dekker [65](2005) presented the scenario aggregation to determine a robust airline fleet composition for dynamic capacity allocation. This two-stage MILP model searches for a solution balanced between alternative scenarios. A large drawback again is that multi-period planning is not an option. Another two-stage stochastic programming example is the work of List, Wood, Nozick, Turnquist, Jones, Kjeldgaard, and Lawton [66](2003), this model includes uncertainty in demand and operating conditions and focuses on robust optimization by risk measurements. As the example used in the report is very small, considering larger cases could result in high computational effort.

Khoo and Teoh [67](2014) presented a model where probabilistic dynamic programming is used to make optimal aircraft fleet decisions. The stochastic demand is based on the stochastic demand index (SDI) which models random events on demand. A drawback is the really small case used.

Repko and Santos [68](2017) proposes an innovative multi-period modeling approach to solve the airline fleet planning problem under demand uncertainty. The model uses a scenario tree approach and determines different scenarios and probabilities. A mixed integer linear model is used to find the optimal fleet for each scenario. This method can provide flexible multi-period fleet plans and therefore has an increased robustness.

Based on the combination of the fleet planning model of Bazargan and Hartman [62] and the stochastic programming techniques of Listes and Dekker [65], Carreira, Lulli, and Antunes [69](2017) created a two-stage stochastic integer model to find the best possible purchase or leasing strategy in order to supply demand. It is chosen to restrict the model to two phases as the study is to examine the interaction between buying and leasing. The authors propose an integration with a network design model for future work.

The three step methodology of Sa, Santos, and Clarke [70](2020) generates a robust fleet that is able to supply any stochastic demand. The model of Repko and Santos [68] used a predetermined set of probabilities and scenario realizations, but this model employed an autoregressive process, the mean-reverting Ornstein-Uhlenbeck process, to sample demand evolutions.

Focussing on environmental impact of the fleet planning, Khoo and Teoh [71](2014) proposed a bi-objective optimization model. Both green performance, defined as the Green Fleet Index, and the profit are optimized over a multi-stage period. A bi-objective model with concurrent objectives can result in a Pareto solution, where a trade off in objectives should be made.

Demand uncertainty is a popular topic within stochastic models, but also other uncertainties are taken into account. An example of fuel uncertainty is presented in the model of Naumann and Suhl [72](2013). However, this two-stage model does not present fleet planning but schedule planning and route frequency optimization. Lately, fuel price uncertainty is also included in fleet planning by Geursen [73](2021).

### SOLUTION TECHNIQUES

In order to solve the designed models discussed above, different solution methods have been proposed. The art of obtaining a solution started with the heuristic method, given by Polya [74](1957). This method focuses on getting a solution rather than an optimal one, where the solution is formed based on comparable situations. To find an optimal solution of the problem, the Simplex method was introduced by Nash [75](2000). This method is used for example by Dantzig and Fulkerson [51] and Fetter [54] and is the foundation for many solution techniques that followed. The first was Gomory [76](1958), who extended the Simplex method to integer variables. In 1960 the Dantzig & Wolfe Decomposition method is presented. This method could handle larger scale problems by solving subproblems with the Simplex method. This decomposition method uses the column generation method. Land and Doig [78](1960) introduced the Branch-and-Bound method where variables only can take discrete values and the technique is not limited to integer programming problems. A drawback of this method is the size of the branches which lead to computational problems. Therefore, Dakin [79](1965) proposed a revised Branch-and-Bound method where the amount of branches is narrowed and thus more feasible to solve.

A variation on the Dantzig & Wolfe Decomposition method is presented by Benders [80](1962) and is known as the Benders Decomposition method. In this method the original problem is divided into a main and second problem and solved separately while new constraints are added compared to the version of Dantzig and Wolfe [77]. This method is known as row generation.

A variation on the Branch-and-Bound (B&B) method is presented by Gomory [81](1963): the Branch-and-Cut method, where cutting planes are added to the B&B method. Cutting planes are formed by constraints and provide an elimination of unfeasible solutions as quick as possible.

Alternative solving methods are Piecewise Linear Approximation, the L-shaped method and Lagrangian Relaxation. Piecewise Linear Approximation is presented by Gould [55](1969), where the original problem presented with functions of the objective, variables and constraints. In this way a non-linear problem can be solved with linear programming methods. Geoffrion [82](1974) proposed the Lagrangian Relaxation method, where some constraints are removed and inserted as a penalty in the objective function. This makes the problem easier to solve and provides a good approximate solution.

Next to these solving methods, some methods are especially created to solve stochastic programming models. Examples are the L-shaped method, the Stochastic Quasi-Gradient method, Scenario Aggregation and the Stochastic Decomposition method.

Van Slyke and Wets [83](1969) published the L-shaped method, which is a variation on the Benders Decomposition. The idea is to approximate the non-linear term in the objective.

Ermoliev [84](1969) presents the Stochastic Quasi-Gradient (SQG) method. This method is proposed for models which include uncertainty as no exact values of objective or constraints functions are required.

Rockafellar and Wets [85](1991) proposed Scenario Aggregation in order to solve stochastic problems. Different future scenarios, based on uncertainties, are defined and optimal solutions are found to these scenarios.

Higle and Sen [86](1991) combined the work of Van Slyke and Wets [83] and Ermoliev [84] and presents the Stochastic Decomposition method in order to solve large scale stochastic programming models.

When the model includes multiple stages, and thus an evolution of the variables over time, solving a (non-)linear problem is not enough. In order to obtain a solution for a multi-stage model, dynamic programming is required. This could for example be a stochastic model where uncertainty develops over time. The first dynamic programming model was presented by Bellman [87](1954). He presented the characteristics such as the state space, the decision space and the outcome space at every time point. The value of being in a certain state is evaluated, also known as the Bellman equation. With time, the dynamic programming models became more and more complex, and the desire to reduce computational time and increase solvability grows. This lack of solvability is due to the "curse of dimensionality" of dynamic programming. Therefore, Approximate Dynamic Programming (ADP) is introduced. Within ADP the value of a specific state is approximated instead of calculated. Powell [88](2007) presents an overview of the different algorithms to estimate these values by ADP.

## 3.2. NETWORK PLANNING

In this section, the network planning models will be presented. With the goal to evaluate the current airline network and possible enhancements, airline network optimisation models are developed. The demand for the network and available aircraft for operating the network are taken into account.

One of the first models is the one of Aykin [89](1995), who proposed an interactive method to solve the hub locations, routing and service types with a heuristics approach. Focussing specifically on the airline industry; Jaillet, Song, and Yu [90](1996) presented the airline network design. They introduced an innovative flow-based linear model for designing networks presenting minimum cost and their associated frequencies, considering local demands and predicted the cost effectiveness of a hub. The model includes a single airline with a fixed market share. Different policies are proposed in three basic integer linear programming models together with heuristic schemes.

Simultaneously with a growing demand for air transportation, the impact of airport capacity constraints is taken into account by Evans, Schafer, and Dray [91](2008). By combining the network optimization and schedule development the airline profit was maximized. Additionally, spill and recapture of passengers becomes more important, and Wang, Klabjan, and Shebalov [92](2014) presented a capacity planning and network design model which incorporates the spill and recapture effects.

Furthermore, studies have been done to evaluate the chosen airline networks. Lederer and Nambimadom [93](1998) presents a detailed study regarding different network types and schedules, to obtain understanding of network choices. The influence of distances, demand and frequencies on the profit of the airline is evaluated. Results show that hub, direct, subtour and tour network can each be optimal for selected parameters. Next, conclusions include that direct service has the lowest schedule frequency and highest schedule reliability. Furthermore, the paper shows that congestion at the hub has a relatively small effect on the optimal network design. Another evaluation is done by Wojahn [94](2001) who evaluated different airline networks on their cost minimization. The demand in this evaluation was generated by the gravity model. Especially the use of a multi-hub network is discussed, which is identified as not cost minimizing. This network is established by economic and operating forces, such as asymmetric costs, airport congestion and competition. Bing [95](2014) developed metrics to evaluate the efficiency and reliability of the network topologies and applies this to the aviation network of China Southern Airlines. Additionally he provides suggestions for optimizing the aviation network.

## 3.3. NETWORK & FLEET PLANNING WITH INTEGRATION OF AIRCRAFT DESIGN

Since airline network choice and fleet choice are in the same time span and related to each other, models have been developed that combine these planning phases. An example of this type of model is given in the airline planning course of Santos [96]. The model includes a set of potential aircraft to include in the fleet and potential airports to include in the network. By deciding the frequency of an aircraft for a specific route in this network, both choices on fleet and network can be made. Here, the frequency can thus be zero, which means that aircraft type combined with that route is not contributing to the optimal solution and therefor is not chosen.

Besides combining network and fleet choice in one model, the desire is to create new aircraft designs, as electrified aircraft for regional purpose are not yet realised. Previously, models have been designed in order to find the optimal aircraft design based on a specific mission or airline network. For example; Roth and Crossley [97](1998), Isikveren [98](2002), Cavalcanti, de Mattos, and Paglione [99](2006) and Allan, Lyrio, Machado, Cavalcanti, Mattos, and Paglione [100](2006) designed a commercial transport aircraft for a specified mission. Additionally, Bower and Kroo [101](2008) constructed a multi-objective aircraft optimization by including airplane emissions. A model to choose the suited airliner for an existing airline network is established by Siqueira, Loureiro, and Mattos [102](2009). Recent work is done by Mattos, Fregnani, and Magalhães [103](2018) where a multi-disciplinary approach is elaborated for the design of optimal airplane configurations suited for a desired airline network. Besides the minimization of cost, the Total Network Yield is maximized.

The aircraft design optimization models will result in an optimal aircraft fleet for the given mission or network, but a yet to be designed network is lacking. In order to optimize both aircraft design and network design, these models should be integrated. The coupling of network- and aircraft design often leads to a Mixed-Integer, Non Linear Programming (MINLP) formulation. Crossley, Mane, and Nusawardhana [104](2004) investigated this problem as "System of Systems" design problem where a mix of existing systems and yet-to-be-determined systems should be established. In this paper: a simple problem using an airline wishing to investigate in how a new, yet-to-be-designed aircraft will impact the fleet operating cost, provides an example. Different solving approaches where considered. The approach solving the MINLP problem generate solutions at high computational effort. Secondary, the response surface approach is used, and good solutions where attained at much lower computational cost. The final approach was the decomposition approach, which is used already in multidisciplinary optimization (MDO), here an “allocation domain” and an “aircraft design domain” are present and solutions are generated at lower computational costs. The conclusion is that for the allocation of variable resources the MDO-motivated decomposition approach is promising. In later research, Crossley and Mane [105](2005) applied the method to two airlines, and the MINLP approach and MDO-motivated decomposition approach were both applied, again the decomposition approach is favoured due to lower computational effort. In 2007, using a similar problem, Mane, Crossley, and Nusawardhana [106](2007) stated that the traditional MINLP approach could be used for small size problems, but when the size increases the MDO decomposition approach is required to solve the problem.

Meanwhile, Taylor and de Weck [107](2006) showed the benefits of optimizing both the network design and the vehicle design at the same time. The case was an overnight package delivery between cities with a fixed demand where the vehicle optimization used a simplified model based on Breguet Range equation. The capacity and demand requirements of the network where solved by a Simulated Annealing algorithm with an embedded linear programming solver. Results showed a minimum of ten percent improvement in cost compared to the network design using a set of pre-defined aircraft.

The aircraft design is a long-term decision, regarding the long creating process, and should therefore be suited as best as possible to the future airline network. Nusawardhana and Crossley [108](2009) investigated the long-term fleet assignment and the impact on aircraft design. As high-fidelity dynamic models for real problems are lacking, generic dynamic models based on various assumptions are used. Following, Davendralingam and Crossley [109](2009) build upon this work by incorporating passenger demand models.

Braun, Wicke, Koch, and Wunderlich [110](2011) focussed on a specific aircraft technology: a natural laminar flow aircraft. Using different future aircraft designs provide various optimal networks for three future scenarios of an existing airline. The network evaluation caused by this aircraft technology is presented.

Hwang, Roy, Kao, Martins, and Crossley [111](2015) concentrated on creating an efficient algorithm for solving simultaneous allocation-mission optimization problems. First the integration of aircraft mission analysis and allocation models is done within a computational framework using the adjoint method for gradient-based optimization. Then the Mixed-Integer allocation mission optimization focussed on allocation only and is solved by the branch-and-bound method. Results show that this approach efficiently finds good local optima. Hwang and Martins [112](2015) extended this work to a larger network with 128-routes. Later, Hwang and Martins [113](2016) wants to integrate both aircraft, route and mission variables. A solution for this complex approach is obtained by a gradient-based optimization with a parallel computational framework. This is again done for the 128-route network with accounting for next generation technologies. As earlier work does not totally capture the coupling between aircraft design and allocation, Roy and Crossley [114](2016) introduced the MINLP problem to solve it. As no existing generalized MINLP solver is able to address the problem, a framework based on Efficient Global Optimization (EGO) is used. To extend this method, Roy, Moore, Hwang, Gray, Crossley, and Martins [115](2017) proposed a new algorithm for solving the MINLP problem combining branch and bound, Efficient Global Optimization, Kriging Partial Least Squares, and gradient-based optimization.

Furthermore, Roy, Crossley, Moore, Gray, and Martins [116](2018) included the operator use into account, as this new system should be used alongside other existing systems, this interaction should be optimized. The subsystems are aircraft design, airline operations and revenue management and the solution is posed as a monolithic optimization problem. Based on the EGO-like optimization, here the A Mixed Integer Efficient Global Optimization (AMIEGO) framework is used.

In recent models additional details are encountered. Alexandre, Fregnani, De Mattos, and Hernandes [117](2020) presented a complex integrated network approach where both the aircraft family of three aircraft designs and the air transport networks are simultaneously optimized. The passenger demand is based on the gravity model. The candidate aircraft designs are generated via a genetic algorithm, which allows a preselection of candidate aircraft based on network profit and direct operating costs. The author states that the candidate aircraft are more complex and sophisticated than utilized before, as over 60 aircraft parameters are included regarding: geometry, topology, propulsion, environmental constraints, certification and performance requirements. Airport characteristics are included and additional noise and emissions constraints of airports could be enforced without much difficulty according to the author. With this information, the second step of the model is the network optimization task. A linear programming model determines the optimal network for these fleet options and detects the configuration where profit is maximized. In order to do this; passenger demand, average ticket price, aircraft fleet capacity, range and operational cost should be known. This work is extended by Fregnani [118](2020) by not only considering the profit from the network, but also the cashflow of the manufacturer.

Within these integrated network and aircraft design models, also other model characteristics can be included. In models mentioned, the demand is often based on the current situation or gravity model and thus deterministic. A stochastic or uncertain demand is taken into consideration by Jansen and Perez, extended to uncertainties in passenger demand over multiple years [119](2013) [120](2014) [121](2016). Also Davendraingam and Crossley [122](2011) took uncertainty into account to present risk and uncertainty of the optimal aircraft design and airline network. Later, this is translated to profit and risk belonging to the serving particular demand itineraries [123](2014).

An important note to this section is that all the models mentioned above are showing the design of conventional, fuel consuming, aircraft. No models yet exist that take into account electrified aircraft in the optimization model.

## 3.4. SUMMARY

In this chapter, the models for fleet planning, network planning and aircraft design are combined and examined. The chapter is completed with an overview of the models found in literature.

For fleet planning, a lot of models have been developed. Starting from 1954, the interest to determine the fleet composition to optimize the airlines financial situation has grown. First, small deterministic models dominated the exploration. But with increasing computational power, larger models could be developed. Within the deterministic models obtaining a solution is at this moment convenient. The challenge within these models is to determine the right values for the input parameters and taking realistic constraints into account.

Stochastic fleet planning models were introduced around 2000. Over the last years, a lot of different approaches have been tried to obtain the best solutions with encounting uncertainty. Not one "best" approach to stochastic two-stage or multi-stage planning models have been found, different approaches such as Scenario Aggregation [64][65], a Stochastic Demand Index [67], Scenario Tree [68] and a Tree Step Methodology [70] are proposed to implement uncertainty. The challenge within stochastic fleet planning models is to implement the uncertainty correctly. This requires a good estimation of the possible scenarios and their probability. Furthermore, models with the integration of another objective, in this case green performance, have been created [71]. Within a bi-objective model a trade off between environmental impact and cost can be done considering a Pareto Frontier.

For network planning, less literature is found. This could be due to the inflexibility of the airline network structure; as the airline network is highly influenced by other existing airline networks it is more difficult to make a change in network structure than in fleet structure for an airline. Models have been established to analyze the profitability of routes and of using hubs [89][90]. In the literature search, often a connection with the flight schedule or the flight frequencies is obtained [90] [91].

Since airline network choice and fleet choice are in the same time span and related to each other, models have been developed that combine these planning phases, such as the one presented in the airline planning course of Santos [96]. Besides combining network and fleet choice in one model, the desire is to create new aircraft designs, as electrified aircraft for regional purpose are not yet realised. The focus will go to models where the optimal aircraft and fleet design is combined with the network design. Coupling these aspects, leads to a Mixed-Integer Non-Linear Programming formulation. As solving a MINLP formulation generates solutions at high computational effort, alternative approaches have been refined a highlighted in literature. Approaches were a response surface approach approach [104], the multidisciplinary optimization (MDO) decomposition approach [104], a Simulated Annealing approach [107], a generic approach [108], a gradient-based approach combined with branch-and-bound [111], an Efficient Global Optimization (EGO) approach [114], a combination of branch-and-bound, EGO, Kriging Partial Least Squares and gradient-based optimization [115] approach and a Mixed

Integer Efficient Global Optimization (AMIEGO) approach [116]. The MDO-motivated decomposition approach was relatively popular due to its low computational effort for larger scale problems.

In recent integrated models, more and more aircraft design details are taken into account. Yet it is important to notice that no electrified aircraft designs are optimized with these models.

# Conclusion

As stated in the Introduction, airlines should endeavor to reduce the environmental impact of their business. One method to do this is to integrate electrified aircraft in the airline fleet. To realize this, electrified aircraft need to be incorporated in the long-term strategic planning of airlines. Within this literature study, relevant literature to the implementation of electrified aircraft to the current regional airline operations in Europe has been considered. The goal of the subsequent project is to determine the optimal combination of using electrified aircraft and the regional airline operations in Europe. Results will provide a selected electrified aircraft fleet together with optional network enhancements.

First, the long-term strategic planning of airlines is analyzed in Section The Planning Framework. This consists of the fleet planning and network development. Within the fleet planning phase a known airline network is used and within the network development phase a known fleet is used. As the goal is to both optimize the fleet and the network, both planning phases are taken into account.

For regional airlines in Europe, the current network structures are studied in Section Regional airline network Europe. It is concluded that the network structures and objectives of these airlines can differ, some have the objective to serve a larger airline and some have the goal to operate independently. In order to set up an airline network development model, the goal of that specific airline (or airline type) should be taken into account.

In the Section Electrified aircraft, the electrified operations are studied. Different classifications within electrified aircraft are made. If the desire is to power the aircraft with batteries, fully-electric or hybrid-electric options exist. For the electrified aircraft, the feasibility is related to the required specific power and required specific battery energy. If an aircraft is desired for regional operations, the aircraft will require a capacity from 4 to 100 seats. For this capacity, the use of fully-electric aircraft is beyond optimistic. Therefore, hybrid-electric aircraft will provide a more feasible solution for the future.

Another way in which the electrified aircraft impact the airline operations is in terms of changed turnaround time. Section Airport infrastructure argues that the charging of electrified aircraft should take place with a Battery Swapping Station (optionally in combination with a Battery Recharging Station) in order to be feasible due to the long charging times of the batteries. The impact on the turnaround time depends on the permission to swap batteries while passengers are inside the aircraft.

For the development of a long-term strategic airline planning model to incorporate the electrified operations, different types of planning models have been analyzed in Chapter Planning models. First of all: the fleet planning models, for this planning phase many models are developed. The goal of this phase is to obtain an optimal fleet for a given airline (network). Both deterministic and stochastic models are covered. Furthermore, the environmental impact of the fleet is included in models with a Green Fleet Index (GFI) and used as an additional objective besides the regular cost or profit based objective.

Network planning studies the profitable routes and hubs within a airline network with a specific fleet. As a specific fleet is not yet defined within this project, network planning alone is not enough to serve the goal of this project. Network planning with a yet undefined fleet can be found in network & fleet planning models, where both the airline network and the airline fleet is optimized. In order to include a yet to be designed aircraft, such as an electrified aircraft, the network&fleet optimization model should include aircraft design optimization. This type of model serves the goal of the subsequent project, but a drawback occurs when solving this model. A Mixed-Integer Non-Linear programming model is created, which requires high effort to solve. Different alternative solving approaches have been proposed in literature, but not one "best" solving method is found. Furthermore, the models reviewed do not incorporate electrified aircraft so far.

Thus, for the thesis project the focus can be on three different models. The fleet planning model can provide an optimal fleet composition and fleet replacement strategy over time for an existing airline (network). Over the years, experience is build within these type of models. Bi-objective models are developed to include the environmental aspect and uncertainty is included in the stochastic models. Beside the fleet planning model, the network & fleet planning model is an option for the subsequent project. The advantage of this model is that the airline network is optimized as well. In order to include yet to be determined aircraft types into the model, the aircraft design should be integrated. This is done throughout literature, but not yet one "best" approach to this problem has been formulated. Furthermore, a drawback of these models is a lacking integration of multiple objectives or uncertainty. For all type of planning models, experience with integrating electrified aircraft in the fleet is not found and therefor shows a gap in literature.

The involvement of electrified aircraft into these planning models will be a relevant addition to current literature and the environmental development of airlines. In the thesis project, it would be interesting to integrate two objectives in order to focus on environmental impact besides the airlines financial situation. Furthermore, two objectives allow for a Pareto solution where the trade off between environmental impact and cost can be analyzed. Another way to study the impact on different objectives is by doing sensitivity studies. Thereby, as the focus is on the implementation of electrified aircraft rather than on estimating the future demand, it would be additional but not necessary to use stochastic models.

# BIBLIOGRAPHY

[1] U. Nations, *The paris agreement,* (2015).

[2] G. based Air Transport Action Group, *Aviation's impact on the environment,* .

[3] R. N. A. C. (NLR) and S. A. Economics, *Destination 2050,* .

[4] K. T. M. N. S. N. L. P. Thomson R., Baum M. and B. N., *Think:act, navigating complexity, aircraft electrical propulsion - onwards and upwards,* (2018).

[5] P. Belobaba, A. Odoni, and C. Barnhart, *The Global Airline Industry* (John Wiley & Sons, 2009).

[6] B. Santos, *Lecture 1: Introduction, planning framework and demand analysis,* (2020).

[7] FlightConnections, *Route map airlines,* (2021).

[8] Wideroe, *Route map,* (2021).

[9] D. A. Transport, *Our routes,* .

[10] AirlineRouteMaps, *Iberia regional air nostrum,* .

[11] B. J. Brelje and J. R. Martins, *Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts, models, and design approaches,* Progress in Aerospace Sciences **104**, 1 (2019).

[12] J. M. Rheaume and C. Lents, *Energy storage for commercial hybrid electric aircraft,* in *SAE 2016 Aerospace Systems and Technology Conference* (SAE International, 2016).

[13] ICAO, *Environmental report 2016,* (2016).

[14] E. National Academies of Sciences and Medicine, *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions* (The National Academies Press, Washington, DC, 2016).

[15] R. Jansen, C. Bowman, A. Jankovsky, R. Dyson, and J. Felder, *Overview of nasa electrified aircraft propulsion (eap) research for large subsonic transports,* in *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, https://arc.aiaa.org/doi/pdf/10.2514/6.2017-4701 .

[16] N. Xue, W. Du, J. R. R. A. Martins, and W. Shyy, *Lithium-ion batteries: Thermomechanics, performance, and design optimization,* in *Handbook of Clean Energy Systems* (American Cancer Society, 2015) pp. 1–16, https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781118991978.hces225 .

[17] C. Pornet, C. Gologan, P. C. Vratny, A. Seitz, O. Schmitz, A. T. Isikveren, and M. Hornung, *Methodology for sizing and performance assessment of hybrid energy aircraft,* Journal of Aircraft **52**, 341 (2015), https://doi.org/10.2514/1.C032716 .

[18] J. Ausserer, *Integration, Testing, and Validation of a Small Hybrid-Electric Remotely-Piloted Aircraft*, Ph.D. thesis (2012).

[19] A. Isikveren, S. Kaiser, C. Pornet, and P. Vratny, *Pre-design strategies and sizing techniques for dual-energy aircraft,* Aircraft engineering and aerospace technology **86**, 525 (2014).

[20] M. F. H. Reynard de Vries and R. Vos, *Range equation for hybrid-electric aircraft with constant power split,* Journal of Aircraft **57** (2020).

[21] Eviation, *Alice commuter,* (2021).

[22] L. A. D. N. Ampaire, *This la company is developing all-electric, zero-emission airplane,* (2021).

[23] S. Stückl, J. Toor, and H. Lobentanzer, *Voltair - the all electric propulsion concept platform - a vision for atmospheric friendly flight,* **4**, 2737 (2012).

[24] M. Hornung, A. Isikveren, M. Cole, and A. Sizmann, *Ce-liner - case study for emobility in air transportation,* (2013).

[25] Wright, *Wright 1 technology,* (2021).

[26] D. F. Finger, R. de Vries, R. Vos, C. Braun, and C. Bil, *A comparison of hybrid-electric aircraft sizing methods,* in *AIAA Scitech 2020 Forum*.

[27] XTI, *Xti tri-fan 600,* (2021).

[28] Z. Aero, *Zunum aero: Aircraft,* (2021).

[29] UNIFIER19, *Unifier19, community friendly miniliner,* (2021).

[30] Ampaire, *Meet the eco otter sx,* (2021).

[31] Y. Fefermann, C. Maury, C. Level, K. Zarati, J.-P. Salanne, C. Pornet, B. Thoraval, and A. Isikveren, *Hybrid-electric motive power systems for commuter transport applications,* (2016).

[32] N. Rossi, *Conceptual design of hybrid-electric aircraft,* (2017).

[33] K. R. Antcliff and F. M. Capristan, *Conceptual design of the parallel electric-gas architecture with synergistic utilization scheme (pegasus) concept,* in *18th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*.

[34] Airbus, *E-fan x, a giant leap towards zero-emission flight,* (2021).

[35] S. M. Jones, W. Haller, and M. Tong, *An n+3 technology level reference propulsion system,* (2017).

[36] J. Zamboni, R. Vos, M. Emeneth, and A. Schneegans, *A method for the conceptual design of hybrid electric aircraft,* in *AIAA Scitech 2019 Forum*.

[37] M. Hoogreef, R. Vos, R. de Vries, and L. L. Veldhuis, *Conceptual assessment of hybrid electric aircraft with distributed propulsion and boosted turbofans,* in *AIAA Scitech 2019 Forum*.

[38] R. de Vries, M. Hoogreef, and R. Vos, *Preliminary sizing of a hybrid-electric passenger aircraft featuring over-the-wing distributed-propulsion,* in *AIAA Scitech 2019 Forum*.

[39] J. R. Welstead, J. Felder, M. D. Guynn, B. Haller, M. Tong, S. M. Jones, I. Ordaz, J. R. Quinlan, and B. Mason, *Overview of the nasa starc-abl (rev. b) advanced concept,* (2017).

[40] H. Kim, J. Felder, M. Tong, J. Berton, and W. Haller, *Turboelectric distributed propulsion benefits on the n3-x vehicle,* Aircraft Engineering and Aerospace Technology **86**, 558 (2014).

[41] S. Sahoo, X. Zhao, and K. Kyprianidis, *A review of concepts, benefits, and challenges for future electrical propulsion-based aircraft,* (2020).

[42] C. E. Riboldi, L. Trainelli, F. Bigoni, F. Salucci, and A. Rolando, *Switching to electric propulsion: Fleet and infrastructure sizing,* (2019).

[43] J. Shim, R. Kostecki, T. Richardson, X. Song, and K. Striebel, *Electrochemical analysis for cycle performance and capacity fading of a lithium-ion battery cycled at elevated temperature,* Journal of Power Sources **112**, 222 (2002).

[44] F. Salucci, L. Trainelli, R. Faranda, and M. Longo, *An optimization model for airport infrastructures in support to electric aircraft,* in *2019 IEEE Milan PowerTech* (2019) pp. 1–5.

[45] P. Newsroom, *Ultra-high-power charging technology for the electric vehicle of the future,* (2018).

[46] C. Friedrich and P. Robertson, *Hybrid-electric propulsion for aircraft,* Journal of Aircraft **52**, 176 (2015), https://doi.org/10.2514/1.C032660 .

[47] C. Y. Justin, A. P. Payan, S. I. Briceno, B. J. German, and D. N. Mavris, *Power optimized battery swap and recharge strategies for electric aircraft operations,* Transportation Research Part C: Emerging Technologies **115**, 102605 (2020).

[48] F. Salucci, L. Trainelli, C. E. Riboldi, and A. L. Rolando, *Sizing of airport recharging infrastructures in support to a hybrid-electric fleet,* in *AIAA Scitech 2021 Forum* (2021).

[49] F. Salucci, L. Trainelli, C. E. Riboldi, and A. L. Rolando, *Optimal sizing and operation of airport infrastructures in support of electric-powered aviation,* (2021).

[50] M. Schmidt, A. Paul, M. Cole, and K. O. Ploetner, *Challenges for ground operations arising from aircraft concepts using alternative energy,* Journal of Air Transport Management **56**, 107 (2016), growing airline networks -Selected papers from the 18th ATRS World Conference, Bordeaux, France, 2014.

[51] G. B. Dantzig and D. R. Fulkerson, *Minimizing the number of tankers to meet a fixed schedule,* Naval Research Logistics Quarterly **1**, 217 (1954), https://onlinelibrary.wiley.com/doi/pdf/10.1002/nav.3800010309 .

[52] D. Kirby, *Is your fleet the right size?* Journal of the Operational Research Society **10**, 252 (1959), https://doi.org/10.1057/jors.1959.25 .

[53] J. K. Wyatt, *Optimal fleet size,* Journal of the Operational Research Society **12**, 186 (1961), https://doi.org/10.1057/jors.1961.30 .

[54] R. B. Fetter, *A linear programming model for long range capacity planning,* Management Science **7**, 372 (1961).

[55] J. Gould, *The size and composition of a road transport fleet,* OR **20**, 81 (1969).

[56] C. C. New, *Transport fleet planning for multi-period operations,* Operational Research Quarterly (1970-1977) **26**, 151 (1975).

[57] D. P. Shube and J. W. Stroup, *Fleet Planning Model*, Tech. Rep. (Institute of Electrical and Electronics Engineers (IEEE), 1975).

[58] M. Etschmaier, *Projects and implementations in the schedule development process of an airline,* in *Technical Report No. 17* (Department of Industrial Engineering, University of Pittsburgh Pittsburgh ..., 1973).

[59] R. W. Simpson, *Scheduling and routing models for airline systems*, Tech. Rep. ([Cambridge, Mass.]: Massachusetts Institute of Technology, Flight ..., 1969).

[60] G. Schick and J. Stroup, *Experience with a multi-year fleet planning model,* Omega **9**, 389 (1981).

[61] H. R. Sayarshad and K. Ghoseiri, *A simulated annealing approach for the multi-periodic rail-car fleet sizing problem,* Computers & Operations Research **36**, 1789 (2009).

[62] M. Bazargan and J. Hartman, *Aircraft replacement strategy: Model and analysis,* Journal of Air Transport Management **25**, 26 (2012).

[63] T. H. Oum, A. Zhang, and Y. Zhang, *Optimal demand for operating lease of aircraft,* Transportation Research Part B: Methodological **34**, 17 (2000).

[64] O. Listes and R. Dekker, *A scenario aggregation based approach for determining a robust airline fleet composition*, Tech. Rep. (2002).

[65] O. Listes and R. Dekker, *A scenario aggregation–based approach for determining a robust airline fleet composition for dynamic capacity allocation,* Transportation Science **39**, 367 (2005).

[66] G. F. List, B. Wood, L. K. Nozick, M. A. Turnquist, D. A. Jones, E. A. Kjeldgaard, and C. R. Lawton, *Robust optimization for fleet planning under uncertainty,* Transportation Research Part E: Logistics and Transportation Review **39**, 209 (2003).

[67] H. L. Khoo and L. E. Teoh, *An optimal aircraft fleet management decision model under uncertainty,* Journal of Advanced Transportation **48**, 798 (2014).

[68] M. G. Repko and B. F. Santos, *Scenario tree airline fleet planning for demand uncertainty,* Journal of Air Transport Management **65**, 198 (2017).

[69] J. S. Carreira, G. Lulli, and A. P. Antunes, *The airline long-haul fleet planning problem: The case of tap service to/from brazil,* European Journal of Operational Research **263**, 639 (2017).

[70] C. A. Sa, B. F. Santos, and J.-P. B. Clarke, *Portfolio-based airline fleet planning under stochastic demand,* Omega **97**, 102101 (2020).

[71] H. L. Khoo and L. E. Teoh, *A bi-objective dynamic programming approach for airline green fleet planning,* Transportation Research Part D: Transport and Environment **33**, 166 (2014).

[72] M. Naumann and L. Suhl, *How does fuel price uncertainty affect strategic airline planning?* Operational Research **13**, 343 (2013).

[73] I. Geursen, *Fleet planning under demand and fuel price uncertainty using actor-critic reinforcement learning,* (2021).

[74] G. Polya, *How to solve it: A new aspect of mathematical method* (Princeton University Press, 1957).

[75] J. Nash, *The (dantzig) simplex method for linear programming,* Computing in Science Engineering **2**, 29 (2000).

[76] R. Gomory, *Outline of an algorithm for integer solutions to linear programs,* Bulletin of the American Mathematical Society **64**, 275 (1958).

[77] G. B. Dantzig and P. Wolfe, *Decomposition principle for linear programs,* Operations Research **8**, 101 (1960).

[78] A. H. Land and A. G. Doig, *An automatic method of solving discrete programming problems,* Econometrica **28**, 497 (1960).

[79] R. J. Dakin, *A tree-search algorithm for mixed integer programming problems,* The computer journal **8**, 250 (1965).

[80] J. F. Benders, *Partitioning procedures for solving mixed-variables programming problems,* Numerische mathematik **4**, 238 (1962).

[81] R. E. Gomory, *An algorithm for integer solutions to linear programs,* Recent advances in mathematical programming **64**, 14 (1963).

[82] A. M. Geoffrion, *Lagrangean relaxation for integer programming,* in *Approaches to integer programming* (Springer, 1974) pp. 82–114.

[83] R. M. Van Slyke and R. Wets, *L-shaped linear programs with applications to optimal control and stochastic programming,* SIAM journal on applied mathematics **17**, 638 (1969).

[84] Y. M. Ermoliev, *On the method of generalized stochastic gradients and quasi-fejér sequences,* Cybernetics **5**, 208 (1969).

[85] R. T. Rockafellar and R. J.-B. Wets, *Scenarios and policy aggregation in optimization under uncertainty,* Mathematics of operations research **16**, 119 (1991).

[86] J. L. Higle and S. Sen, *Stochastic decomposition: An algorithm for two-stage linear programs with recourse,* Mathematics of Operations Research **16**, 650 (1991).

[87] R. Bellman, *The theory of dynamic programming,* Bulletin of the American Mathematical Society **60**, 503 (1954).

[88] W. B. Powell, *Approximate Dynamic Programming: Solving the curses of dimensionality*, Vol. 703 (John Wiley & Sons, 2007).

[89] T. Aykin, *The hub location and routing problem,* European Journal of Operational Research **83**, 200 (1995).

[90] P. Jaillet, G. Song, and G. Yu, *Airline network design and hub location problems,* Location Science **4**, 195 (1996), hub Location.

[91] A. Evans, A. Schafer, and L. Dray, *Modelling airline network routing and scheduling under airport capacity constraints,* in *The 26th Congress of ICAS and 8th AIAA ATIO* (2008).

[92] D. D. Wang, D. Klabjan, and S. Shebalov, *Attractiveness-based airline network models with embedded spill and recapture,* Journal of Airline and Airport Management **4**, 1 (2014).

[93] P. J. Lederer and R. S. Nambimadom, *Airline network design,* Operations Research **46**, 785 (1998).

[94] O. W. Wojahn, *Airline network structure and the gravity model,* Transportation Research Part E: Logistics and Transportation Review **37**, 267 (2001).

[95] D. Bing, *Reliability analysis for aviation airline network based on complex network,* Journal of Aerospace Technology and Management **6**, 193 (2014).

[96] B. Santos, *Lecture 3: Network and fleet planning,* (2020).

[97] G. Roth and W. Crossley, *Commercial transport aircraft conceptual design using a genetic algorithm based approach,* in *7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization* (1998).

[98] A. Isikveren, *Quasi-Analytical Modelling and Optimisation Techniques for Transport Aircraft Design*, Ph.D. thesis (2002).

[99] J. Cavalcanti, B. de Mattos, and P. Paglione, *Optimal conceptual design of transport aircraft,* in *11th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference* (2006).

[100] J. Allan, A. Lyrio, J. Machado, T. Cavalcanti, B. S. D. Mattos, and P. Paglione, *Paper cit06-0546 wing and airfoil optimized design of transport aircraft,* (2006).

[101] G. Bower and I. Kroo, *Multi-objective aircraft optimization for minimum cost and emissions over specific route networks,* in *The 26th Congress of ICAS and 8th AIAA ATIO* (2008).

[102] L. Siqueira, V. Loureiro, and B. Mattos, *The suited airliner for an existing airline network,* in *50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* (2009).

[103] B. Mattos, J. A. Fregnani, and S. Magalhães, *An innovative approach for optimal airplane design encompassing an airline network,* (2018) pp. 324–375.

[104] W. Crossley, M. Mane, and A. Nusawardhana, *Variable resource allocation using multidisciplinary optimization: Initial investigations for system of systems,* in *10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference* (2004).

[105] W. Crossley and M. Mane, *System of systems inspired aircraft sizing applied to commercial aircraft / airline problems,* in *AIAA 5th ATIO and16th Lighter-Than-Air Sys Tech. and Balloon Systems Conferences* (2005).

[106] M. Mane, W. A. Crossley, and Nusawardhana, *System-of-systems inspired aircraft sizing and airline resource allocation via decomposition,* Journal of Aircraft **44**, 1222 (2007).

[107] C. Taylor and O. de Weck, *Integrated transportation network design optimization,* in *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* (2006).

[108] N. Nusawardhana and W. Crossley, *Concurrent aircraft design and variable resource allocation in large scale fleet networks,* in *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)* (2009).

[109] N. Davendralingam and W. Crossley, *Concurrent aircraft design and airline network design incorporating passenger demand models,* in *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)* (2009).

[110] M. Braun, K. Wicke, A. Koch, and T. Wunderlich, *Analysis of natural laminar flow aircraft based on airline network design and fleet assignment,* in *11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference* (2011).

[111] J. Hwang, S. Roy, J. Kao, J. R. R. A. Martins, and W. A. Crossley, *Simultaneous aircraft allocation and mission optimization using a modular adjoint approach,* in *56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* (2015).

[112] J. T. Hwang and J. R. R. A. Martins, *Parallel allocation-mission optimization of a 128-route network,* in *16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference* (2015).

[113] J. T. Hwang and J. R. R. A. Martins, *Allocation-mission-design optimization of next-generation aircraft using a parallel computational framework,* in *57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* (American Institute of Aeronautics and Astronautics, 2016).

[114] S. Roy and W. A. Crossley, *An ego-like optimization framework for simultaneous aircraft design and airline allocation,* in *57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* (2016).

[115] S. Roy, K. Moore, J. T. Hwang, J. S. Gray, W. A. Crossley, and J. R. R. A. Martins, *A mixed integer efficient global optimization algorithm for the simultaneous aircraft allocation-mission-design problem,* in *58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* (2017).

[116] S. Roy, W. A. Crossley, K. T. Moore, J. S. Gray, and J. R. R. A. Martins, *Next generation aircraft design considering airline operations and economics,* in *2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* (2018).

[117] J. Alexandre, T. Fregnani, B. S. De Mattos, and J. A. Hernandes, *An innovative approach for integrated airline network and aircraft family optimization,* Chinese Journal of Aeronautics **33**, 634 (2020).

[118] J. A. Fregnani, *Simultaneous airline network and aircraft optimization considering manufacturer´s net present value,* (2020).

[119] P. W. Jansen and R. E. Perez, *Coupled optimization of aircraft design and fleet allocation with uncertain passenger demand,* in *2013 Aviation Technology, Integration, and Operations Conference* (2013).

[120] P. W. Jansen and R. E. Perez, *Robust coupled optimization of aircraft design and fleet allocation for multiple markets,* in *AIAA/3AF Aircraft Noise and Emissions Reduction Symposium* (2014).

[121] P. W. Jansen and R. E. Perez, *Coupled optimization of aircraft families and fleet allocation for multiple markets,* Journal of Aircraft **53**, 1485 (2016), https://doi.org/10.2514/1.C033646 .

[122] N. Davendraingam and W. Crossley, *Robust optimization of aircraft design and airline network design incorporating econometric trends,* in *11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference* (2011).

[123] N. Davendralingam and W. Crossley, *Robust approach for concurrent aircraft design and airline network design,* Journal of Aircraft **51**, 1773 (2014), https://doi.org/10.2514/1.C032442 .

# III

## Research Methodologies

previously graded under AE4010

# Impact of regional airline planning on the electrified aircraft design

By Noa Zuijderwijk, 4462343

Air Transport Operations, Control and Operations

## Executive Summary

In order to stimulate aircraft manufacturers and airlines to adapt electrified aircraft, the most suitable electrified aircraft for current operations should be determined. The focus of this work is on the regional airlines in Europe. Airlines currently plan their aircraft fleet and network in the long-term strategic planning phases: fleet planning and network development. This thesis project will propose an optimization model which integrates the electrified aircraft design with these airline planning phases in order to find an aircraft which suits the airline.

A literature review is done to the integration of aircraft design and long-term airline planning, which exposed the problem to be Mixed-Integer and Non-Linear and requires much effort to solve. This thesis project will implement the aircraft design by creating a manual feedback loop to evolve the aircraft designs. This feedback loop will create a linear programming model which could be solved without much effort and in the time span of this project.

The design of electrified aircraft will be studied throughout literature and simulation models and will be used as input for the optimization model. Furthermore, the feedback loop will create additional aircraft designs based on the favoured designs of the model.

When the results are verified and validated, the information can be used by aircraft manufacturers to develop electrified aircraft suitable for regional operations in Europe and will therefore stimulate the implementation of electrified aircraft in the airline industry.

## 1. Introduction

Worldwide, efforts to reduce the climate change are in progress [41]. As the air transport is responsible for around 2% of the $CO_2$ emission in 2018 and the industry is still growing (disregarding the Covid pandemic impact) [6], it is important give attention to new measures that reduce the emissions of aviation. To have a reduction in emissions, improvements in aircraft and engine technologies can be performed [43]. For this work, the focus is on the adaption of electrified aircraft.

In order to replace conventional aircraft by electrified aircraft, the airline network should be aligned with the new aircraft designs. The goal the project is to find the electrified aircraft designs which best suit the airlines. The development of electrified aircraft is starting at small aircraft designs and slowly expanding to larger ones [62] as the battery technology improves. To implement electrified aircraft as soon as possible, first the airline industry using smaller aircraft, thus regional airlines will be chosen. This work will concentrate on the regional airline network in Europe. Combining the electrified aircraft possibilities with the desires of the regional airlines in Europe should result in improved aircraft designs that suit these airlines and their network development. In order to realize this plan, the Project Plan is presented.

To start with, the literature review in section 2 presents the current state-of-the-art in both airline planning and electrified aircraft operations. Then the research questions and objectives are discussed in section 3. This is followed by the methodology in section 4. The experimental set-up is given in section 5 and the results, outcome and relevance of the project in section 6. Thereafter in section 7, the project planning is presented. In the end, the conclusions of this thesis project plan are provided in section 8.

# 2. Literature Review

In this section, the literature found in the literature study will be summarized and presented. First background information on airline planning and the characteristics of regional airlines in Europe will be given in section 2.1. Then the electrified operations are identified in terms of aircraft designs and required airport infrastructure in section 2.2. Thereafter, the development of planning models is presented in section 2.3.

## 2.1. Background

### 2.1.1 Airline planning framework

The airline planning framework [55] presents various steps in the airline planning process. Within this project, the focus is on the long-term strategic planning decisions: fleet planning and network development. In the fleet planning phase, the acquisition and retirement planning of the aircraft fleet is determined with the goal to optimize the airline's financial position. The airline network is often assumed known in this planning phase. In the network development phase, the profitable routes and network structure for the airline will be detected regarding a known aircraft fleet. Specific fleet planning and network development models will be discussed in section 2.3.

### 2.1.2 Regional airlines Europe

In this section, the European regional airlines are analyzed. Regional airlines have arisen with the goal to connect locations with a smaller demand to the network of larger airlines. The airlines can be subdivided based on their network size. Small regional airlines have only a few connections and medium size regional airlines have connections within their own country and occasionally with neighbouring cities. Large size regional airlines connect to multiple cities throughout Europe and very large sized airlines serve almost every country in Europe. For some airlines, the purpose to serve larger airlines is visible in the topology, as quite diverse not-connecting routes are served. Some other (mostly) larger European airlines are operating more independently and a network structure such as Hub-and-Spoke or Point-to-Point structure can be obtained.

## 2.2. Electrified operations

In this section, the conditions of operating electrified aircraft are discussed. Starting with the state-of-the-art of electrified aircraft and then going to the required infrastructure for electrified operations.

### 2.2.1 Electrified aircraft

In order to implement electrified aircraft in the airline planning, the available aircraft designs and challenges should be studied. At this moment, the largest realized electrified aircraft has a capacity of four [9]. In order to serve regional airlines, the current state-of-the-art of electrified aircraft designs with a minimum of four seats is considered. Furthermore, the aircraft designs have been classified in different groups, the fully-electric and hybrid-electric aircraft designs. Within the hybrid-electric aircraft designs a distinction between turboelectric, serial hybrid-electric and parallel hybrid-electric can be made based on their degree-of-hybridization [4] [29]. Conceptual aircraft designs are presented for these different groups and a major point of discussion is the feasibility of the aircraft designs.

The feasibility of the design is highly related to the specific battery energy and peak power required. The current realized specific energy of an aircraft reaches to 207 Whr/kg for the Airbus E-Fan [27]. For the future: NAE expects the specific energy to reach 400-600 Whr/kg at pack level by 2035 [40] and NASA predicts a future battery technology that can deliver 400-1000 Whr/kg at pack level [47][31]. Conceptual aircraft designs often have a required specific energy of 500-750 Whr/kg [60][17][3][32], which is stated optimistic but possibly feasible for the future [66][15]. Moreover, aircraft designs with a required battery energy of 2000 Whr/kg at pack level are presented [23], but this feasibility should be questioned [19].

When analyzing these electrified aircraft, note that in the turboelectric aircraft designs still fuel is used to produce energy and fly the aircraft [9]. Batteries replace a part of the fuel energy in serial-hybrid or parallel-hybrid architecture or completely in a fully-electric architecture. Within the aircraft designs which (partly) fly on batteries and are suitable for regional airline operations (more than 4 seats), the fully-electric aircraft desire significantly more specific battery energy than hybrid-electric ones. As increasing the specific energy is already challenging, it is more likely for hybrid-electric aircraft to become feasible in the future than fully-electric aircraft.

Furthermore, for electrified aircraft, a trade-off occurs between amount of batteries (and thus energy), range and seats as presented in the conceptual designs of Finger et al. [19]. When it is desired to increase the range of the aircraft, the amount of batteries needs to increase to provide the required energy. This increase in batteries raises the weight of the aircraft and to remain the same MTOW, less passengers can be transported. This works the other way around as well, when it is desired to transport more passengers either the battery capacity needs to increase, or the range decreases.

### 2.2.2 Airport infrastructure

In order to make an airline planning including electrified operations, the impact of changing infrastructure on airline operations needs to be determined. When looking to the airline operations, the airport operations influence the turnaround time and the turnaround cost of the aircraft. In order to evaluate this impact, the method of charging is important. Charging can be done by a Battery Recharging Station (BRS) which is similar to the current refuelling stations or by a Battery Swapping Station (BSS) which swaps the empty batteries for charged ones [48]. As the charging capacity of the BRS at this moment leads to too long charging times [52][21], this method is at this moment unfit for electrified airport operations. The BSS is therefore the only option feasible at this moment, and research in literature has been focused on this method or a combination of both methods [48][33][53][54].

Schmidt, Paul, Cole, and Ploetner [57] presented the turnaround times for two new aircraft types: the SUGAR Volt, a hybrid-electric aircraft, and the Ce-liner, a fully-electric aircraft. With a BSS and the allowance to swap batteries while passengers are on board, both turnaround times require 34 minutes. If the swapping can not take place when passengers are on board, this turnaround time rises to 58 minutes for the SUGAR Volt and 48 minutes for the Ce-liner. The reference aircraft is the A320-2035, a future concept of the A320-2012, and has a turnaround time of 41 minutes.

Information on the changed cost for the turnaround are lacking in literature. As the energy price varies during the day, the time of charging will impact the turnaround cost.

## 2.3. Planning models

In this section, the development of long-term strategic planning models in literature is been presented. Fleet planning models and network development models will be discussed separately. Subsequently, the integrating of aircraft design into these planning phases is studied. Note that the objective of this project is to obtain electrified aircraft designs which best suit the regional airline operations in Europe.

### 2.3.1 Fleet planning models

Over the years, many fleet planning models have been developed. The goal of fleet planning is to determine the optimal aircraft (fleet) for the future within a given airline network. Since 1954, deterministic fleet planning models were developed [13], started with a single-stage linear model that could be solved by hand. The model evolved by taking into account different expressions for the demand [65] and a distinction between aircraft leasing and buying [18]. Including an inhomogeneous fleet was made possible by Gould [22] and multi-periodicity in the models of New [42] and Shube and Stroup [58]. Application to real airline planning is done in a following model of Schick and Stroup [56], and presented the added value of computer automation to manual planning.

As models evolve, the desire to include uncertainty increases and stochastic fleet planning models are established. One of the first is the two-stage stochastic model of Oum, Zhang and Zhang [45]. Different approaches are used to include uncertainty, such as the scenario aggregation based approach by Listes and Dekker [37][38] and probablistic dynamic programming by Khoo and Teoh [34]. A multi-period stochastic model is presented by Repko and Santos [46]. The approaches to include stochasticity are still unfolding at this moment. Furthermore, other additions to the model have been made. Such as the inclusion of the environmental impact by Khoo and Teoh [35].

### 2.3.2 Network development models

The goal of network planning (or development) is to determine the optimal routes to fly with an available fleet and to evaluate the current airline network and possible enhancements. One of the first models is the one of Aykin [5] who solved hub locations with a heuristics approach. Jaillet, Song and Yu [30] focused on the airline industry and presented the airline network design. Additions to the model are made by; Evans, Schafer and Dray [16] who included airport capacity constraints and Wang, Klabjan and Shebalov [63] who included spill and recapture of passengers. The evaluation of networks is presented in literature by Lederer and Nambimadom [36], Wojahn [64] and Bing [7].

### 2.3.3 Network & fleet development models including aircraft design

Besides the network and fleet development, the objective of this project is to find an optimal set of aircraft that suit the regional airline operations. In literature, various models have been designed in order to find the optimal aircraft design based on a specific mission [49][28][10][2]. Extensions to multiple objectives have been done which included aircraft emissions by Bower and Kroo[8] and to a larger airline network by Siqueiras, Fregnani, and Magalhães [59]. Note that these models are fleet planning models with a given network and a yet to be designed set of aircraft.

Later, these aircraft design models have been extended to yet to be determined airline networks. In these models, the network design is simultaneaously optimized. The coupling of network- and aircraft design leads to a Mixed-Integer, Non Linear Programming (MINLP) formulation. Different approaches to the problem have been presented in literature; such as the decomposition approach of multidisciplinary optimization (MDO) [12][11] and the traditional MINLP approach for small size problems [39]. Taylor and de Weck [61] showed the benefits of optimizing both the network and aircraft design at the same time and Nusawardhana and Crossley [44] and Davendralingam and Crossley [14] investigated the long-term fleet assignment and the impact on aircraft design. Different studies have been done to create an efficient algorithm and various approaches are presented, but not one "best" approach could be obtained [24][25][26][50][51]. Additional details are encountered in later work: Alexandre, Fregnani, De Mattos and Hernandes [1] presented a complex integrated network approach where both the aircraft family of three aircraft designs and the air transport networks are simultaneously optimized. Later, this work has included the cashflow of the manufacturer [20].

## 2.4. Conclusion

In the literature study, the conditions for introducing electrified aircraft into the airline planning are studied. The background gives information about the planning framework and the current situation of regional airlines in Europe. The section on electrified operations presents the available conceptual electrified aircraft designs and the corresponding challenges together with the impact of infrastructure adjustments on the airline operations. Section 2.3 presented the different models used so far in long-term strategic airline planning and showed the integration of aircraft design and airline planning.

In order to translate the literature to a project, the focus should go to one type of model. In fleet planning models, the development of the current fleet into the electrified fleet will be determined. In network planning models, the target is on the network development instead. In literature, an integration of network and aircraft design has been done, which integrates the fleet planning as well. As the goal of this project is to obtain electrified aircraft designs which best suit the regional airlines in Europe, this last type of models are most suitable. A drawback of including aircraft design into the planning model is that a Mixed-Integer, Non-Linear Programming (MINLP) formulation is gained which is hard to solve. This could be simplified by making a manual iterative process where a new fleet is chosen. Furthermore, as the goal of this project is to obtain the future situation rather than the development to the future situation, the model does not have to include multi-periodicity. Moreover, the goal is not to include uncertainty and therefor a deterministic single-stage model can be chosen. A choice can be made to include an additional environmental objective.

# 3. Research Objectives and Questions

This section consists out of two main parts: the research objective and the research questions. To formulate the objective and questions, the problem statement is formulated as:

> In order to reduce the environmental impact of aviation, airlines and manufacturers should be stimulated to integrate electrified aircraft. Presenting electrified aircraft design(s) which best suit their operations, based on optimal network and fleet development, will lower the threshold of implementation and therefore stimulate airlines and manufacturers.

## 3.1. Research Objective

> "To achieve (a) electrified aircraft designs which suit the operations of European regional airlines by means of (b) integrating the aircraft design in a network optimization model".

## 3.2. Research Question(s)

The main question of this project will be:

> How can suitable electrified aircraft designs for European regional airlines be determined by integrating the aircraft design in an airline network optimization model?

Subquestions have been established to obtain the answer for the main research question.

1. How can a network optimization model for European regional airlines with electrified operations be established?
    - (a) Is there an existing model to build forward upon?
    - (b) What is/are the objective(s)? Regarding the aims of European regional airlines? Environmental objective?
    - (c) What is the desired output?
    - (d) What are the input parameters?
    - (e) What are the constraints? (airline and airport)
    - (f) Is the running time reasonable for this project?
2. How can the aircraft design be implemented into the model?
    - (a) How is aircraft design implemented in earlier work?
    - (b) How can the aircraft design evolve?
    - (c) How will the initial database of electrified aircraft be established?
    - (d) Which aircraft characteristics should be known?

(e) What electrified aircraft designs will be present in the database?

    i. What type of electrified aircraft? Fully-electric / serial hybrid-electric / parallel hybrid-electric / turboelectric?

    ii. What aircraft are “feasible” regarding their battery technology?

(f) Is the available information sufficient as input for the model?

    i. What information is missing? And how can this be obtained?

(g) What information will feeded back to the aircraft database?

(h) What happens in one iteration?

3. What is the result of implementing electrified aircraft in the model and how are the solutions determined and compared?

    (a) How is the output of the model from different iterations compared to each other?

    (b) How is/are the objective(s) visible and interpretable in the models output?

4. How is the model verification done?

    (a) How can the behaviour of the model be evaluated?

        i. How does the model react on given inputs and constraints? Is that expected?

        ii. How does the model work compared to existing models?

    (b) How can a sensitivity analysis be performed?

5. How is the model validation done?

    (a) What components of the model need validation?

    (b) What case study would be suitable for the validation?

    (c) What is obtained from the validation?

6. How can the results of the model be translated into future recommendations for aircraft manufacturers and airlines who aim to implement electrified aircraft?

    (a) What is the relation between the airline network and the aircraft design regarding the different objectives?

    (b) Can the results be generalized for different airline networks in Europe?

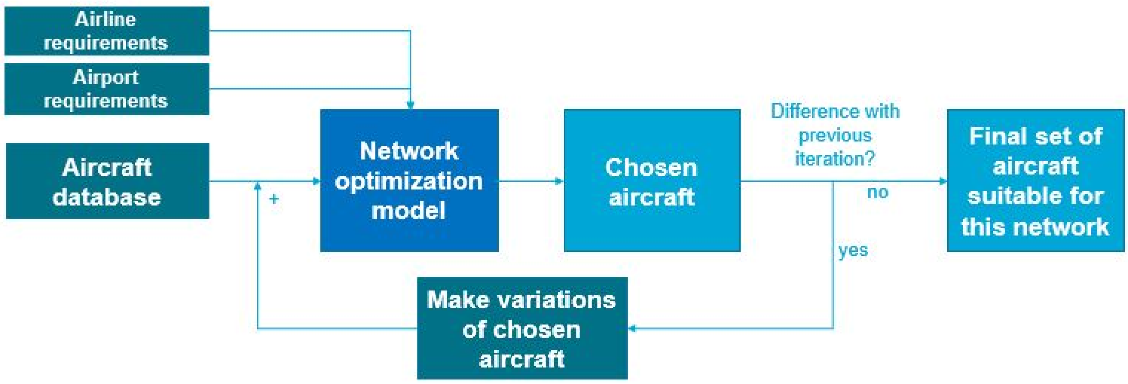
    (c) What is lacking in this research? (recommendations for additional future work)

Answering these research questions is the objective of this thesis. The questions are translated into different steps that will be taken in the next section, Methodology.

# 4. Methodology

As stated in the introduction, the objective of the project is to implement electrified aircraft designs into the long-term airline planning in order to determine suitable electrified aircraft for European regional airline operations. Throughout literature, aircraft design have been integrated with airline network development. This integration gives a Mixed-Integer Non-Linear Programming which requires much effort to solve. Within this project, an iterative version to integrate aircraft design and airline network planning is proposed and performed for regional airline networks in Europe. This is achieved by setting up an optimization model which performs the steps presented in the block diagram in Figure 1.

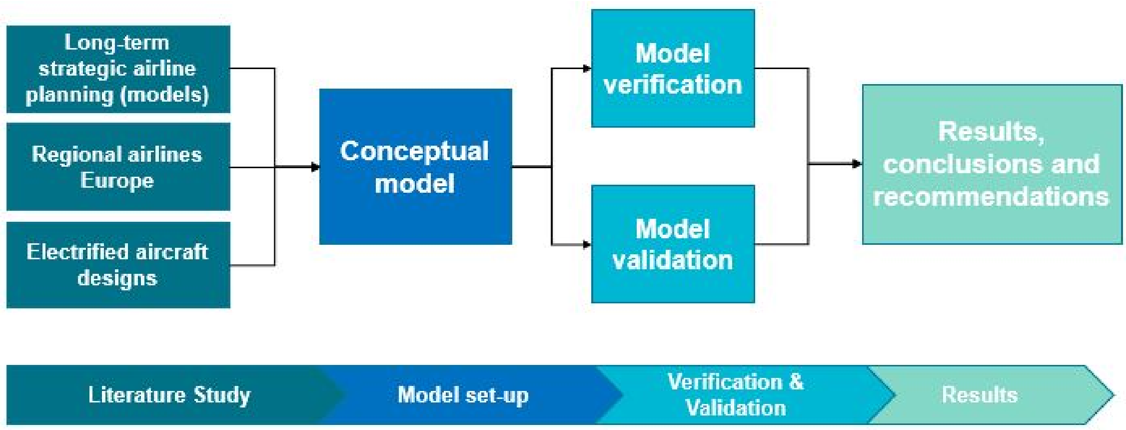
Figure 1: Block diagram of model




The input of the model will consist of the airline and airport requirements together with the first set of the electrified aircraft database. In the network optimization model, the aircraft designs which give an optimal network performance given the objectives will be selected. In order to find the electrified aircraft designs which best suit the airline operations, a feedback loop is created. Here, chosen aircraft designs will be slightly modified and added to the initial aircraft database. Again the network optimization model is run and the most suitable aircraft designs for this network are presented. This will repeat until no new output is given by the model.

This conceptual model should be verified and validated before conclusions can be made. The overall research framework of this thesis project is given in Figure 2.

Figure 2: Research Framework



## 5. Experimental Set-up

The experimental set-up will be discussed for the steps "Literature Study" and "Model set-up" in the research framework. Further information on the "Verification & Validation" and "Results" will be given in the next section: Results, Outcome and Relevance.

The first step is the Literature Study, here information required to set up a conceptual model is acquired. Examples of network optimization models are analyzed, together with their objectives, constraints, assumptions, input and output data. The specifications of an European regional airline and electrified operations are analyzed. Findings are complemented with information required during the meetings with the supervisors of this project.

The model set-up will be performed in Python. As this source is commonly used in Airline planning and other industries and is a free and open software. The input data will be imported from Excel, in order to easily adjust this data for other situations.

## 6. Results, Outcome and Relevance

The result of this project will consist of a final set of electrified aircraft designs that suit the regional airline network in Europe. These aircraft designs are able to serve the required passenger demand while operating under optimization of the objective(s) of this airline. For these selected aircraft designs, different characteristic values such as number of seats and range are presented in the outcome of the model. When the airline has multiple objectives, a Pareto plot can be used to study trade-offs.

In order to use the results of the project, these should first be verified and validated. This will be done in the "Verification & Validation" step in the research framework. The model verification is performed in different ways. This could be by discussing the working principle of the model with the supervisors of the project, visualizing the steps given in the model or checking the model behaviour when adjusting input parameters. Validation of the model is performed by implementing a case study of a real-life European regional airline.

When the model verification and validation is done, the results can be presented. These will be translated to conclusions on this thesis project, the applicability in the real world and recommendations for future research.

The relevance of this project is the stimulation of the development of electrified aircraft in order to reduce the environmental impact of aviation. Aircraft manufacturers want to develop aircraft types that are desired by airlines in order to sell them. The result of this thesis project presents electrified aircraft designs which fulfil the wishes of regional airlines in Europe. As the most suited aircraft designs for their network is chosen, the airlines will be encouraged in using these aircraft types and the threshold to transfer from conventional aircraft to electrified aircraft will be lowered. Aircraft manufacturers can use the outcome to know which aircraft designs are interesting for airlines and can focus on developing the selected types of electrified aircraft designs. Hence the outcome of this project will contribute to the implementation of electrified aircraft in the regional airline industry and will therefore provide a reduction of the environmental impact of aviation.

## 7. Project Planning

For the project planning, first a general planning is presented in Table 1. Here the planned moments for the important meetings and deadlines are established.

A more detailed planning is given in a Gantt chart in Figure 3 in Appendix A. The plan-

Table 1: General project planning

| Phase | Content | Result | Deadline |
|---|---|---|---|
| A | Literature Study (8 weeks)<br>Holiday (1 week) | Kick-off meeting | week 32<br>2021 |
| B | Research Methodologies (1 week)<br>Initial phase (13 weeks)<br>Holiday (2 weeks) | Mid-term meeting | week 48<br>2021 |
| C | Final phase (13 weeks)<br>Holiday (1 week) | Green-light meeting | week 10<br>2022 |
| D | Revise (4 weeks) | Presentation & Defense | week 14<br>2022 |

ning phases can be related to the research framework and model set-up presented in section 4. The important milestones given in the general planning are included in this planning as well. The goal is to set up the complete working model before the Mid-term meeting. The time after this meeting will be used for model validation, verification and processing of the results. Buffer times are included to provide a realistic planning.

## 8. Conclusions

This project plan gives an overview of the thesis project. The larger aim of this project is to stimulate the implementation of electrified aircraft in an airlines fleet in order to reduce the environmental impact of aviation. Therefore, this project will attain suitable aircraft designs for European regional airlines to comply with their operations.

To achieve this, a long-term strategic airline planning model will be modified to implement electrified aircraft and their corresponding operations. As the project has the goal to present the future situation rather than the development to the future situation, the choice has been made to create a single-stage deterministic model. A literature review is done to the integration of aircraft design and long-term airline planning, which exposed the problem to be Mixed-Integer and Non-Linear and requires much effort to solve. This thesis project will implement the aircraft design by creating a manual feedback loop to evolve the aircraft designs. This feedback loop will create a linear programming model which could be solved without much effort.

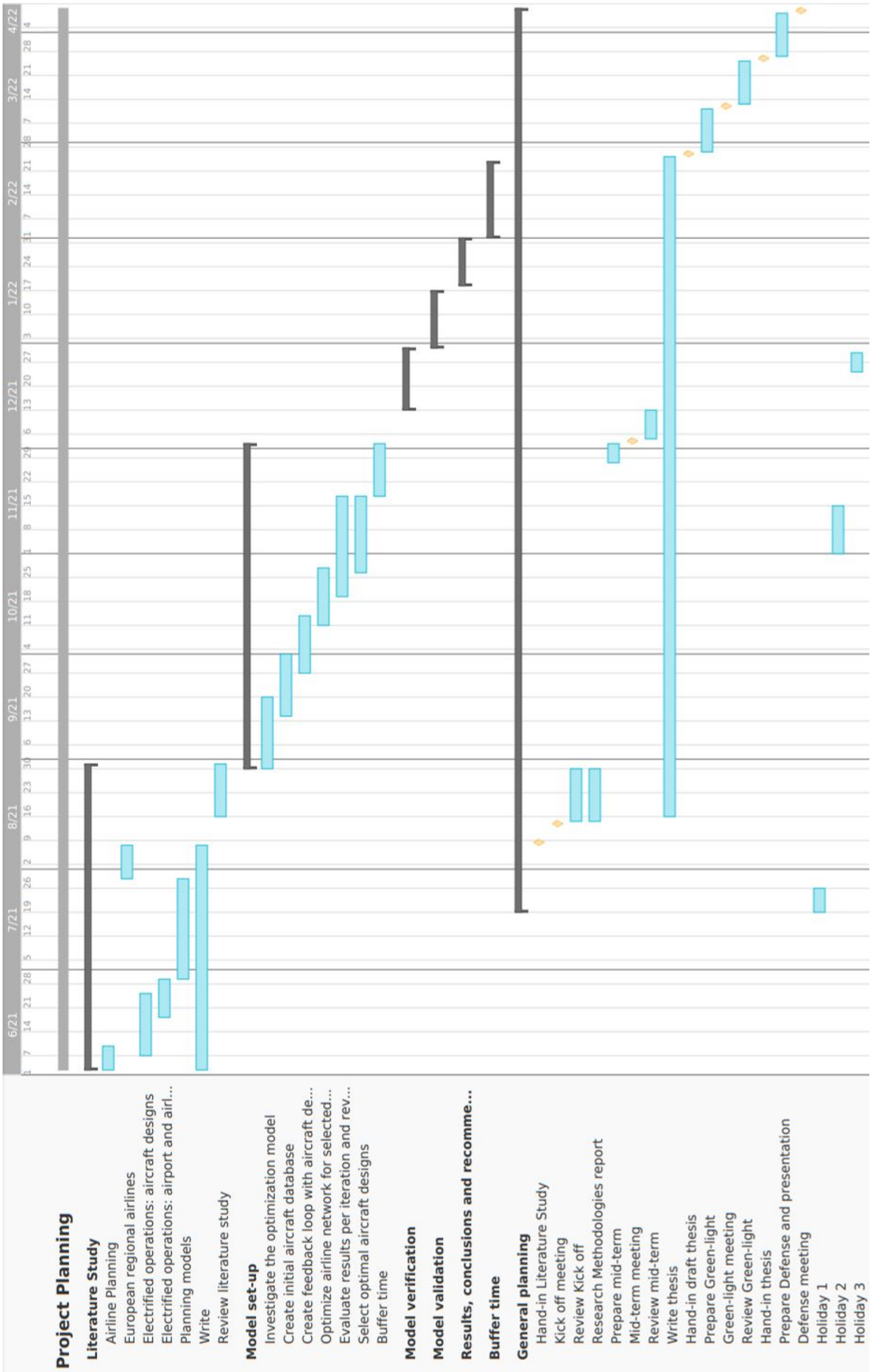
To include electrified aircraft designs into the model, the current state-of-the-art knowledge in electrified aircraft designs and the corresponding airport and airline requirements are analyzed. Challenges occur when there is lacking data or not yet researched subjects. This information should be required in other ways, such as making assumptions or acquiring experience from the supervisors.

The chosen long-term strategic airline planning model is combined with the knowledge about electrified operations and like this, a conceptual model will be developed which finds the electrified aircraft characteristics that best suit the regional airline. Further challenges in this phase are expected when creating the electrified aircraft database and making variations on aircraft designs. Regarding the time, creating these variations will be outside the scope and will be provided by one of the supervisors.

When the results are verified and validated, the information can be used by aircraft manufacturers to develop electrified aircraft suitable for regional operations in Europe and will therefore stimulate the implementation of electrified aircraft.

# A. Gantt Chart

Figure 3: Gantt chart



## References


[1] J. Alexandre, T. Fregnani, B. S. De Mattos, and J. A. Hernandes. An innovative approach for integrated airline network and aircraft family optimization. Chinese Journal of Aeronautics, 33(2):634–663, 2020. ISSN 1000-9361. doi: https://doi.org/10.1016/j.cja.2019.10.004. URL https://www.sciencedirect.com/science/article/pii/S1000936119304042.

[2] J. Allan, A. Lyrio, J. Machado, T. Cavalcanti, B. S. D. Mattos, and P. Paglione. Paper cit06-0546 wing and airfoil optimized design of transport aircraft, 2006.

[3] K. R. Antcliff and F. M. Capristan. Conceptual Design of the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) Concept. doi: 10.2514/6.2017-4001. URL sacd.larc.nasa.gov/wp-content/uploads/sites/102/2017/10/Antcliff_Aviation2017_PEGASUS.pdf.

[4] J. Ausserer. Integration, Testing, and Validation of a Small Hybrid-Electric Remotely-Piloted Aircraft. PhD thesis, 03 2012.

[5] T. Aykin. The hub location and routing problem. European Journal of Operational Research, 83(1):200–219, 1995. ISSN 0377-2217. doi: https://doi.org/10.1016/0377-2217(93)E0173-U. URL https://www.sciencedirect.com/science/article/pii/0377221793E0173U.

[6] G. based Air Transport Action Group. Aviation's impact on the environment. URL https://aviationbenefits.org/environmental-efficiency/aviations-impact-on-the-environment/.

[7] D. Bing. Reliability analysis for aviation airline network based on complex network. Journal of Aerospace Technology and Management, 6:193–201, 05 2014. doi: 10.5028/jatm.v6i2.295.

[8] G. Bower and I. Kroo. Multi-Objective Aircraft Optimization for Minimum Cost and Emissions over Specific Route Networks. 2008. doi: 10.2514/6.2008-8905.

[9] B. J. Brelje and J. R. Martins. Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts, models, and design approaches. Progress in Aerospace Sciences, 104:1–19, 2019. ISSN 0376-0421. doi: https://doi.org/10.1016/j.paerosci.2018.06.004. URL https://www.sciencedirect.com/science/article/pii/S0376042118300356.

[10] J. Cavalcanti, B. de Mattos, and P. Paglione. Optimal Conceptual Design of Transport Aircraft. 2006. doi: 10.2514/6.2006-7022.

[11] W. Crossley and M. Mane. System of Systems Inspired Aircraft Sizing Applied to Commercial Aircraft / Airline Problems. 2005. doi: 10.2514/6.2005-7426.

[12] W. Crossley, M. Mane, and A. Nusawardhana. Variable Resource Allocation Using Multidisciplinary Optimization: Initial Investigations for System of Systems. 2004. doi: 10.2514/6.2004-4605.

[13] G. B. Dantzig and D. R. Fulkerson. Minimizing the number of tankers to meet a fixed schedule. Naval Research Logistics Quarterly, 1(3):217–222, 1954. doi: https://doi.org/10.1002/nav.3800010309. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/nav.3800010309.

[14] N. Davendralingam and W. Crossley. Concurrent Aircraft Design and Airline Network Design Incorporating Passenger Demand Models. 2009. doi: 10.2514/6.2009-6971.

[15] R. de Vries, M. Hoogreef, and R. Vos. Preliminary Sizing of a Hybrid-Electric Passenger Aircraft Featuring Over-the-Wing Distributed-Propulsion. doi: 10.2514/6.2019-1811.

[16] A. Evans, A. Schafer, and L. Dray. Modelling Airline Network Routing and Scheduling under Airport Capacity Constraints. 2008. doi: 10.2514/6.2008-8855.

[17] Y. Fefermann, C. Maury, C. Level, K. Zarati, J.-P. Salanne, C. Pornet, B. Thoraval, and A. Isikveren. Hybrid-electric motive power systems for commuter transport applications. 09 2016.

[18] R. B. Fetter. A linear programming model for long range capacity planning. Management Science, 7(4):372–378, 1961. ISSN 00251909, 15265501. URL http://www.jstor.org/stable/2627057.

[19] D. F. Finger, R. de Vries, R. Vos, C. Braun, and C. Bil. A Comparison of Hybrid-Electric Aircraft Sizing Methods. doi: 10.2514/6.2020-1006.

[20] J. A. Fregnani. Simultaneous airline network and aircraft optimization considering manufacturer´s net present value. 09 2020.

[21] C. Friedrich and P. Robertson. Hybrid-electric propulsion for aircraft. Journal of Aircraft, 52(1):176–189, 2015. doi: 10.2514/1.C032660. URL https://doi.org/10.2514/1.C032660.

[22] J. Gould. The size and composition of a road transport fleet. OR, 20(1):81–92, 1969. ISSN 14732858. URL http://www.jstor.org/stable/3008537.

[23] M. Hornung, A. Isikveren, M. Cole, and A. Sizmann. Ce-liner - case study for emobility in air transportation. 08 2013. ISBN 978-1-62410-225-7. doi: 10.2514/6.2013-4302.

[24] J. Hwang, S. Roy, J. Kao, J. R. R. A. Martins, and W. A. Crossley. Simultaneous aircraft allocation and mission optimization using a modular adjoint approach. 2015. doi: 10.2514/6.2015-0900.

[25] J. T. Hwang and J. R. R. A. Martins. Parallel allocation-mission optimization of a 128-route network. 2015. doi: 10.2514/6.2015-2321.

[26] J. T. Hwang and J. R. R. A. Martins. Allocation-mission-design optimization of next-generation aircraft using a parallel computational framework. In 57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. American Institute of Aeronautics and Astronautics, Jan 2016. doi: 10.2514/6.2016-1662.

[27] ICAO. Environmental report 2016. 2016. URL https://www.icao.int/environmental-protection/Documents/ICAO%20Environmental%20Report%202016.pdf.

[28] A. Isikveren. Quasi-Analytical Modelling and Optimisation Techniques for Transport Aircraft Design. PhD thesis, 05 2002.

[29] A. Isikveren, S. Kaiser, C. Pornet, and P. Vratny. Pre-design strategies and sizing techniques for dual-energy aircraft. Aircraft engineering and aerospace technology, 86: 525–542, 10 2014. doi: 10.1108/AEAT-08-2014-0122.

[30] P. Jaillet, G. Song, and G. Yu. Airline network design and hub location problems. Location Science, 4(3):195–212, 1996. ISSN 0966-8349. doi: https://doi.org/10.1016/S0966-8349(96)00016-2. URL https://www.sciencedirect.com/science/article/pii/S0966834996000162. Hub Location.

[31] R. Jansen, C. Bowman, A. Jankovsky, R. Dyson, and J. Felder. Overview of NASA Electrified Aircraft Propulsion (EAP) Research for Large Subsonic Transports. doi: 10.2514/6.2017-4701. URL https://arc.aiaa.org/doi/abs/10.2514/6.2017-4701.

[32] S. M. Jones, W. Haller, and M. Tong. An n+3 technology level reference propulsion system. 2017.

[33] C. Y. Justin, A. P. Payan, S. I. Briceno, B. J. German, and D. N. Mavris. Power optimized battery swap and recharge strategies for electric aircraft operations. Transportation Research Part C: Emerging Technologies, 115:102605, 2020. ISSN 0968-090X. doi: https://doi.org/10.1016/j.trc.2020.02.027. URL https://www.sciencedirect.com/science/article/pii/S0968090X19310241.

[34] H. L. Khoo and L. E. Teoh. An optimal aircraft fleet management decision model under uncertainty. Journal of Advanced Transportation, 48(7):798–820, 2014.

[35] H. L. Khoo and L. E. Teoh. A bi-objective dynamic programming approach for airline green fleet planning. Transportation Research Part D: Transport and Environment, 33: 166–185, 2014. ISSN 1361-9209. doi: https://doi.org/10.1016/j.trd.2014.06.003. URL https://www.sciencedirect.com/science/article/pii/S1361920914000686.

[36] P. J. Lederer and R. S. Nambimadom. Airline network design. Operations Research, 46 (6):785–804, 1998. ISSN 0030364X, 15265463. URL http://www.jstor.org/stable/222934.

[37] O. Listes and R. Dekker. A scenario aggregation based approach for determining a robust airline fleet composition. Technical report, 2002.

[38] O. Listes and R. Dekker. A scenario aggregation–based approach for determining a robust airline fleet composition for dynamic capacity allocation. Transportation Science, 39(3):367–382, 2005.

[39] M. Mane, W. A. Crossley, and Nusawardhana. System-of-systems inspired aircraft sizing and airline resource allocation via decomposition. Journal of Aircraft, 44(4):1222–1235, 2007. doi: 10.2514/1.26333.

[40] E. National Academies of Sciences and Medicine. Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions. The National Academies Press, Washington, DC, 2016. ISBN 978-0-309-44096-7. doi: 10.17226/23490. URL https://www.nap.edu/catalog/23490/commercial-aircraft-propulsion-and-energy-systems-research-reducing-global-carbo

[41] U. Nations. The paris agreement, 2015. URL https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[42] C. C. New. Transport fleet planning for multi-period operations. Operational Research Quarterly (1970-1977), 26(1):151–166, 1975. ISSN 00303623. URL http://www.jstor.org/stable/3008398.

[43] R. N. A. C. (NLR) and S. A. Economics. Destination 2050. URL https://www.destination2050.eu/.

[44] N. Nusawardhana and W. Crossley. Concurrent Aircraft Design and Variable Resource Allocation in Large Scale Fleet Networks. 2009. doi: 10.2514/6.2009-6977.

[45] T. H. Oum, A. Zhang, and Y. Zhang. Optimal demand for operating lease of aircraft. Transportation Research Part B: Methodological, 34(1):17–29, 2000.

[46] M. G. Repko and B. F. Santos. Scenario tree airline fleet planning for demand uncertainty. Journal of Air Transport Management, 65:198–208, 2017.

[47] J. M. Rheaume and C. Lents. Energy storage for commercial hybrid electric aircraft. In SAE 2016 Aerospace Systems and Technology Conference. SAE International, sep 2016. doi: https://doi.org/10.4271/2016-01-2014. URL https://doi.org/10.4271/2016-01-2014.

[48] C. E. Riboldi, L. Trainelli, F. Bigoni, F. Salucci, and A. Rolando. Switching to electric propulsion: Fleet and infrastructure sizing. 09 2019.

[49] G. Roth and W. Crossley. Commercial transport aircraft conceptual design using a genetic algorithm based approach. 1998. doi: 10.2514/6.1998-4934.

[50] S. Roy and W. A. Crossley. An EGO-like Optimization Framework for Simultaneous Aircraft Design and Airline Allocation. 2016. doi: 10.2514/6.2016-1659.

[51] S. Roy, K. Moore, J. T. Hwang, J. S. Gray, W. A. Crossley, and J. R. R. A. Martins. A Mixed Integer Efficient Global Optimization Algorithm for the Simultaneous Aircraft Allocation-Mission-Design Problem. 2017. doi: 10.2514/6.2017-1305.

[52] F. Salucci, L. Trainelli, R. Faranda, and M. Longo. An optimization model for airport infrastructures in support to electric aircraft. In 2019 IEEE Milan PowerTech, pages 1–5, 2019. doi: 10.1109/PTC.2019.8810713.

[53] F. Salucci, L. Trainelli, C. E. Riboldi, and A. L. Rolando. Sizing of Airport Recharging Infrastructures in Support to a Hybrid-Electric Fleet. 2021. doi: 10.2514/6.2021-1682.

[54] F. Salucci, L. Trainelli, C. E. Riboldi, and A. L. Rolando. Optimal sizing and operation of airport infrastructures in support of electric-powered aviation. 2021.

[55] B. Santos. Lecture 1: Introduction, planning framework and demand analysis, 2020.

[56] G. Schick and J. Stroup. Experience with a multi-year fleet planning model. Omega, 9 (4):389–396, 1981.

[57] M. Schmidt, A. Paul, M. Cole, and K. O. Ploetner. Challenges for ground operations arising from aircraft concepts using alternative energy. Journal of Air Transport Management, 56:107–117, 2016. ISSN 0969-6997. doi: https://doi.org/10.1016/j.jairtraman.2016.04.023. URL https://www.sciencedirect.com/science/article/pii/S096969971630165X. Growing airline networks -Selected papers from the 18th ATRS World Conference, Bordeaux, France, 2014.

[58] D. P. Shube and J. W. Stroup. Fleet planning model. Technical report, Institute of Electrical and Electronics Engineers (IEEE), 1975.

[59] L. Siqueira, V. Loureiro, and B. Mattos. The Suited Airliner for an Existing Airline Network. 2009. doi: 10.2514/6.2009-2206.

[60] S. Stückl, J. Toor, and H. Lobentanzer. Voltair - the all electric propulsion concept platform - a vision for atmospheric friendly flight. 4:2737–2747, 01 2012.

[61] C. Taylor and O. de Weck. Integrated Transportation Network Design Optimization. 2006. doi: 10.2514/6.2006-1912.

[62] K. T. M. N. S. N. L. P. Thomson R., Baum M. and B. N. Think:act, navigating complexity, aircraft electrical propulsion - onwards and upwards, 2018.

[63] D. D. Wang, D. Klabjan, and S. Shebalov. Attractiveness-based airline network models with embedded spill and recapture. Journal of Airline and Airport Management, 4: 1–25, 2014.

[64] O. W. Wojahn. Airline network structure and the gravity model. Transportation Research Part E: Logistics and Transportation Review, 37(4):267–279, 2001. ISSN 1366-5545. doi: https://doi.org/10.1016/S1366-5545(00)00026-0. URL https://www.sciencedirect.com/science/article/pii/S1366554500000260.

[65] J. K. Wyatt. Optimal fleet size. Journal of the Operational Research Society, 12(3):186–187, 1961. doi: 10.1057/jors.1961.30. URL https://doi.org/10.1057/jors.1961.30.

[66] J. Zamboni, R. Vos, M. Emeneth, and A. Schneegans. A Method for the Conceptual Design of Hybrid Electric Aircraft. doi: 10.2514/6.2019-1587.

# IV

## Supporting work

# 1

# Sensitivity analyses on model choices

## 1.1. Maximum route size

In this section, the impacts of some assumptions regarding the model are tested. These assumptions are the maximum number of flights per route and the time limitation of the optimization and have been established to reduce the computational time. However, these assumptions should not have a large effect on the final result. Therefore, the impact of changing these values on the adaptation is studied.

The maximum number of successive flights per route has been set to 3, as increasing this number leads to long computational times. In the results can be obtained that the maximum number of flights in the network is two, and no routes with three successive flights are operated.

With a maximum of three successive flights, 420 routes are generated. When including routes with four successive flights, 900 routes will be added (leads to a total of 1320 routes) and routes with five successive flights lead to 2700 additional options (to a total of 4020 routes).

Due to the computational time, it is not possible to add the routes of four or more flights to the current routes, but it is possible to replace the current routes with only routes of four or more flights. In this section, the impact of changing the available route sizes is studied. Table 1.1 presents the outcomes.

Table 1.1: Results with varying route sizes

| **Optional route size [# flights]** | **Profit (OF) [€]** | **$CO_2$ emission [kg]** | **Fleet** |
|---|---|---|---|
| 4 | no solution | | |
| 5 | out of memory | | |

The results show that the network can not be developed with only routes of four flights. Note that this does not mean that a combination of routes with one, two, or three stops and routes with four (or even more) stops is not preferable. Unfortunately, when the route size is set to 5, and more than 1320 options are entered in the model, there is not enough memory to compute a solution.

## 1.2. Optimization time limit

Further, a time limit for the optimization process has been set at 600 seconds. Due to this limitation, the optimization is cut off before the final solution is obtained. As this is a strategic model, an estimation of the network and fleet is sufficient, however it should be checked if this estimation provides a representative result. Therefore, the impact of changing the time limitation on the network and fleet choice is presented. It is chosen to obtain the effect of a doubled time limit of 1200 seconds and a time limit of 9 hours. Outcomes are presented in Table 1.2.

Table 1.2: Results with varying optimization time limits

| **Time limit** | **Profit (OF) [€]** | **$CO_2$ emission [kg]** | **Fleet** |
|---|---|---|---|
| 1200 s | $-92.7 * 10^4$ | $15.6 * 10^4$ | FE20+1(2), HE28+1(1), HEB48(1), Q400(2) |
| 9 hours | $-92.7 * 10^4$ | $15.6 * 10^4$ | FE20+1(2), HE28+1(1), HEB48(1), Q400(2) |

The results with enlarged computational time lead to the same outcome as a time limit of 600 seconds. Therefore, increasing the time limit has no impact on the network and fleet choice.

# 2
# Sensitivity analysis on fuel and energy consumption of aircraft

The Initiator provides information regarding the fuel and energy consumption of different aircraft types. To see the sensitivity of the network and fleet choice to consumption values, it is chosen to double and halve the consumption per technology type. Results on the network and fleet choice are visualized in Figure 2.1. Performance in profit and $CO_2$ emission is presented in the axes of the graph, and the fleet choice by the colored squares.

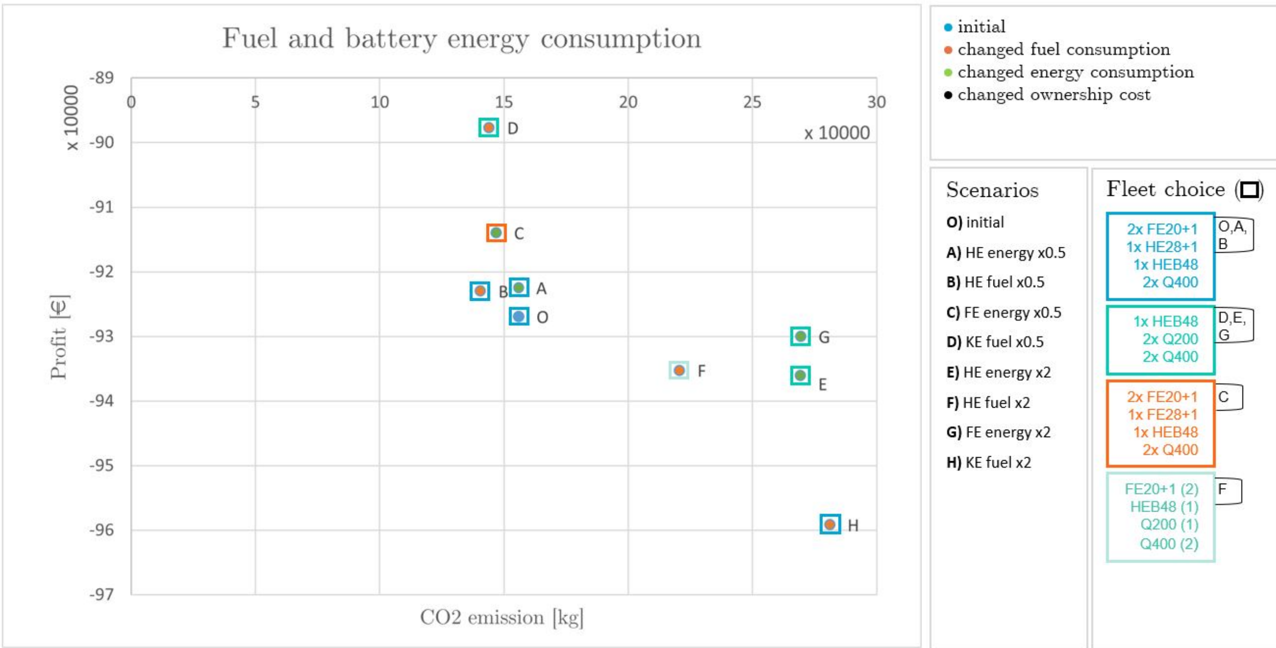



Figure 2.1: Performance with different aircraft consumptions

More kerosene aircraft are chosen when the fuel consumption of kerosene aircraft is decreased, or the consumption of hybrid- and fully-electric aircraft is increased. Lowering the energy consumption of fully-electric aircraft results in a choice for a fully-electric 28-seater instead of a hybrid-electric one. Other adjusted consumption values do not impact the fleet choice. Higher consumption values lead to more cost and vice versa. The value for fuel consumption does not only influence the cost but the $CO_2$ emission as well.

# Bibliography


[1] European Commission. the european green deal, 2020. URL https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.

[2] MAHEPA. Towards the new era of aviation. URL https://mahepa.eu/2021/10/27/towards-the-new-era-of-aviation/.

[3] United Nations. The paris agreement, 2015. URL https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[4] Royal Netherlands Aerospace Centre (NLR) and SEO Amsterdam Economics. Destination 2050. URL https://www.destination2050.eu/.

[5] CORDIS EU research results. Credible hybrid electric aircraft. URL https://cordis.europa.eu/project/id/101007715.