**Master Thesis**

# Evaluation of the Hybrid-Electric Aircraft Project Airbus E-Fan X

Author: Diego Benegas Jayme

Supervisor: Prof. Dr.-Ing. Dieter Scholz, MSME
Submitted: 2019-06-30

*Faculty of Engineering and Computer Science*
*Department of Automotive and Aeronautical Engineering*

DOI:
https://doi.org/10.15488/9353

URN:
https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2019-06-30.012

Associated URLs:
https://nbn-resolving.org/html/urn:nbn:de:gbv:18302-aero2019-06-30.012

© This work is protected by copyright

The work is licensed under a Creative Commons Attribution-ShareAlike 4.0
International License: CC BY-SA
https://creativecommons.org/licenses/by-sa/4.0

Any further request may be directed to:
Prof. Dr.-Ing. Dieter Scholz, MSME
E-Mail see: http://www.ProfScholz.de

This work is part of:
Digital Library - Projects & Theses - Prof. Dr. Scholz
http://library.ProfScholz.de

Published by
Aircraft Design and Systems Group (AERO)
Department of Automotive and Aeronautical Engineering
Hamburg University of Applied Science

This report is deposited and archived:

- Deutsche Nationalbiliothek (https://www.dnb.de)
- Repositorium der Leibniz Universität Hannover (https://www.repo.uni-hannover.de)
- Internet Archive (https://archive.org)
  Item: https://archive.org/details/TextBenegasJayme.pdf

This report has no associated published data in Harvard Dataverse.

# Abstract

**Purpose** - This master thesis evaluates the hybrid-electric aircraft project *E-FAN X* with respect to its economical and environmental performance in comparison to its reference aircraft, the *BAe 146-100*. The *E-FAN X* is replacing one of the four jet engines of the reference aircraft by an electric motor and a fan. A turboshaft engine in the cargo compartment drives a generator to power the electric motor.

**Methodology** - The evaluation of this project is based on standard aircraft design equations. Economics are based on Direct Operating Costs (DOC), which are calculated with the method of the Association of European Airlines (AEA) from 1989, inflated to 2019 values. Environmental impact is assessed based on local air quality ($NO_x$, Ozone and Particulate Matter), climate impact ($CO_2$, $NO_x$, Aircraft-Induced Cloudiness known as AIC) and noise pollution estimated with fundamental acoustic equations.

**Findings** - The battery on board the *E-FAN X* it is not necessary. In order to improve the proposed design, the battery was eliminated. Nevertheless, due to additional parts required in the new configuration, the aircraft is 902 kg heavier. The turboshaft engine saves only 59 kg of fuel. The additional mass has to be compensated by a payload reduced by 9 passengers. The DOC per seat-mile are up by more than 10% and equivalent CO2 per seat-mile are more than 16% up in the new aircraft.

**Research limitations** - Results are limited in accuracy by the underlying standard aircraft design calculations. The results are also limited in accuracy by the lack of knowledge of some data of the project.

**Practical implications** - The report contributes arguments to the discussion about electric flight.

**Social implications** - Results show that unconditional praise given to the environmental characteristics of this industry project are not justified.

# Contents

# List of Figures

# List of Tables

# List of Symbols

| | |
|---|---|
| $A$ | Wing aspect |
| $B$ | Breguet parameter |
| $a$ | Speed of Sound |
| $C_D$ | Drag coefficient |
| $C_{D0}$ | Profile drag coefficient |
| $C_L$ | Lift coefficient |
| $D$ | Drag |
| $E$ | Glide ratio |
| $e$ | Oswald efficiency factor |
| $g$ | Gravity constant |
| $h$ | Height |
| $I$ | Sound intensity |
| $L$ | Lift / Length |
| $M$ | Mach number |
| $m$ | Mass |
| $P$ | Power |
| $R$ | Range |
| $S$ | Surface |
| $T$ | Thrust |
| $t$ | Time |
| $V$ | Velocity / Voltage |
| $W$ | Weight |

## Greek Symbols

| | |
|---|---|
| $\varepsilon$ | Specific power |
| $\rho$ | Density |
| $\eta$ | Efficiency |
| $\mu$ | Friction coefficient |
| $\sigma$ | Electrical conductivity |

## Indices

| | |
|---|---|
| $()_{AE}$ | *AE 2100A* |
| $()_{AF}$ | Airframe |
| $()_{ALF}$ | *Lycoming ALF 502R-5* |
| $()_{alt}$ | alternative |
| $()_{bat}$ | battery |
| $()_{CC}$ | Cabin crew |
| $()_{CLB}$ | Climbing |
| $()_{CR}$ | Cruise |
| $()_{CO}$ | Cockpit crew |
| $()_{DEP}$ | Depreciation |
| $()_{DES}$ | Descend |
| $()_{elec}$ | electrical system |
| $()_{eng}$ | Engine |
| $()_{F}$ | Fuel |
| $()_{FEE}$ | Fees |
| $()_{GND}$ | Ground |
| $()_{INS}$ | Insurance |
| $()_{INT}$ | Interest |
| $()_{L}$ | Landing |
| $()_{M}$ | Maintenance |
| $()_{LOI}$ | Loiter |
| $()_{MA}$ | Missing approach |
| $()_{MPL}$ | Maximum Payload |
| $()_{MTO}$ | Maximum Take Off |
| $()_{N}$ | New configuration |
| $()_{NAV}$ | Navigation |
| $()_{O}$ | Old configuration |
| $()_{OE}$ | Operating Empty |
| $()_{pax}$ | Passengers |
| $()_{PL}$ | Payload |
| $()_{S}$ | Spares |
| $()_{SC}$ | Staff Cost |

| | |
|---|---|
| $()_{SO}$ | Switch off |
| $()_{T}$ | Taxi |
| $()_{T-E}$ | from turboshaft to engine |
| $()_{TO}$ | Take off |
| $()_{W}$ | Wing |
| $()_{X}$ | Maximum |

# List of Abbreviations

| | |
|---|---|
| ACARE | Advisory Council for Aeronautical Research in Europe |
| AFR | Air to Fuel Ratio |
| BPR | Bypass Ratio |
| CF | Charaterization Factors |
| DOC | Direct Operating Costs |
| EI | Emission Index |
| EPNdB | Effective Perceived Noise in deciBels |
| EVTOL | Electrical Vertical Take Off and Landing |
| GWP | Global Warming Potential |
| ICAO | International Civil Aviation Organization |
| LCA | Life-cycle Assessment |
| LTO | Landing and Take Off Cycle |
| MFV | Maximum Fuel Volume |
| MFW | Maximum Fuel Weight |
| MPL | Maximum Payload |
| MTOW | Maximum Take Off Weight |
| NMVOC | Non-Methane Volatile Organic Compound |
| OAPR | Overall Pressure Ratio |
| OEW | Operative Empty Weight |
| PM | Particle Matter |
| PSFC | Power Specific Fuel Consumption |
| RF | Radiative Forcing |
| SRES | Special Report on Emissions Scenarios |
| SPC | Specific Power Consumption |
| TOW | Take Of Weight |
| TSFC | Thrust Specific Fuel Consumption |
| UAT | Urban Air Taxi |
| UAV | Unmanned Aerial Vehicle |
| USD | United States Dollars |

# Definitions

### Climate change

"Variation in the climate system that lasts a period of time long enough to reach a new equilibrum."

### Fly-by-wire

"System that replaces the conventional manual flight controls of an aircraft with an electronic interface"

### Megacities

"Very large city metropolitan area, typically with a population of more than 10 million people."

### Particulate Matter

"All solid and fluid particles in the atmosphere that stay in the air for a while instead of dropping onto ground directly, like soot, smoke, dust or droplets of oil and fuel, with a diameter that ranges from a couple of nanometres up to 100 $\mu m$"

# 1 Introduction

## 1.1 Motivation

Global warming and greenhouse effect are a fact. Each day, the emissions by the humans are growing. Then, sustainable development is the goal, satisfying the current necessities without compromising the capacities of futures generations. The equilibrium between economic growth, caring of the environment and social welfare is required.

The aviation, as one of the human activities over the world, contributes to the global warming and greenhouse effect. The contribution of this sector represents 5% of the total emissions of the human activities (ICSA 2016). Despite not being the main contributor, the problem lies in the growth rate of this sector. It is estimated to keep growing at a rate of 5% per year until 2037 (Airbus 2018; Boeing 2018). For this purpose, the European Union Commission created the *Flightpath 2050*, in order to reduce the emissions (EU 2011). Solutions must be found to reduce the emission without limiting the growth of the sector, and hybrid-electric aircraft seem to be one of the solutions.

Hybrid-electrical aviation is having so much space in the news and newspapers, where this type of aviation is sold as the savior of the aeronautical world. The possibility of flying with batteries, recharged with clean energy, will mean zero emissions. For the large commercial aircraft it is not possible to fly only with batteries, but they can be used together with an engine, in order to reduce the emissions. These reductions will mitigate the growth rate of the aircraft sector, and maybe also will create a new way of transporting with low emissions.

Taking into account all the factors, new ways of aircraft design are required. In this master thesis, an evaluation of a selected hybrid-electric project is done. The aircraft selected for the evaluation is the *E-FAN X*, currently being developed by a partnership between Airbus and Rolls-Royce. When this master thesis began, Siemens was also part of this partnership. But during the development of the project, the relationship between Airbus and Siemens turned on a supplier relationship, instead of a partnership (Hampel 2019). The viability of the *E-FAN X*, and thus, all of these kind of aircraft, can relieve the necessities about the global warming. But first it is necessary to know the viability of this new aircraft. Results are required, in order to known if these sort of aircraft are better, equal or worse than the conventional aircraft.

## 1.2 Title Terminology

### Evaluation

Evaluation is the structured interpretation and giving of meaning to predicted or actual impacts of proposals or results. It looks at original objectives, and at what is either predicted or what was accomplished and how it was accomplished. Regarding this master thesis, two evaluations are done. One is an economic evaluation, a process of identification, measurement and valuation of the inputs and outcomes of two alternative activities, and the subsequent comparative analysis of these. The other is the environmental evaluation, a process of estimating and evaluating significant short-term and long-term effects of a program or project on the quality of the environment of its location

### Hybrid-Electric Aircraft

The term hybrid-electric aircraft could have two meanings. One meaning is related to the aircraft that use two power sources, such as turbine engine and electric motor, to drive the fan (or propeller) on an aircraft—hybrid electric powertrain. The other meaning is related to the aircraft that use the combination of more than one propulsive sources: engines, turboelectric energy generation, fuel cells energy generation, or battery energy storage—hybrid electric propulsion (Bowman 2016).

## 1.3 Objectives

The purpose of the master thesis is to show the necessity of evaluating thoroughly all the electrical aircraft projects in development. For this reason, an evaluation of the *E-FAN X* aircraft, an evolution of the *BAe 146-100*, is realized, in order to bring results to the community. In the *E-FAN X* project, one turbofan of this aircraft will be replaced with an electric motor. This makes the *E-FAN X* an hybrid-aircraft. The evaluation is done in two dimensions of sustainability: economy and environment. To make the assessment, the Direct Operating Costs method is used for the economic dimension. The DOC refer to the expenses incurred directly in the operation of a particular aircraft. For the environmental dimension, the Life-cycle Assessment method is used. The LCA is a technique to assess environmental impacts associated with all the stages of life of a product. This two evaluations together suppose the Eco-Efficiency evaluation of the project. With the results of this two evaluations, some conclusions about this project can be drawn.

## 1.4 Structure of the Master Thesis

This work has been structured as follows:

**Chapter 2:** First, the viability of electrical propulsion is explained. Then, several electrical aircraft projects are mentioned and quickly reviewed.
**Chapter 3:** The transformation of the BAe 146-100 into the E-FAN X is realized.
**Chapter 4:** The economic evaluation of both aircraft is done, showing the different results. The DOC method has been used for this evaluation.
**Chapter 5:** The environmental evaluation is done, thanks to the LCA method.
**Chapter 6:** Final conclusions about the result of this master thesis are gathered in this chapter.

# 2 State of the Art

## 2.1 Viability of Electrical Propulsion

Electrical propulsion is now a reality. But if it wants to be a real alternative, it has to attain the requirements imposed by the commercial flying. All the electric types of propulsion can be gathered in six different types, as it is shown in Figure 2.1.

- Electric
- Hybrid electric
  - Parallel hybrid
  - Series hybrid
  - Series/parallel partial hybrid
- Turboelectric
  - Full turboelectric
  - Partial turboelectric

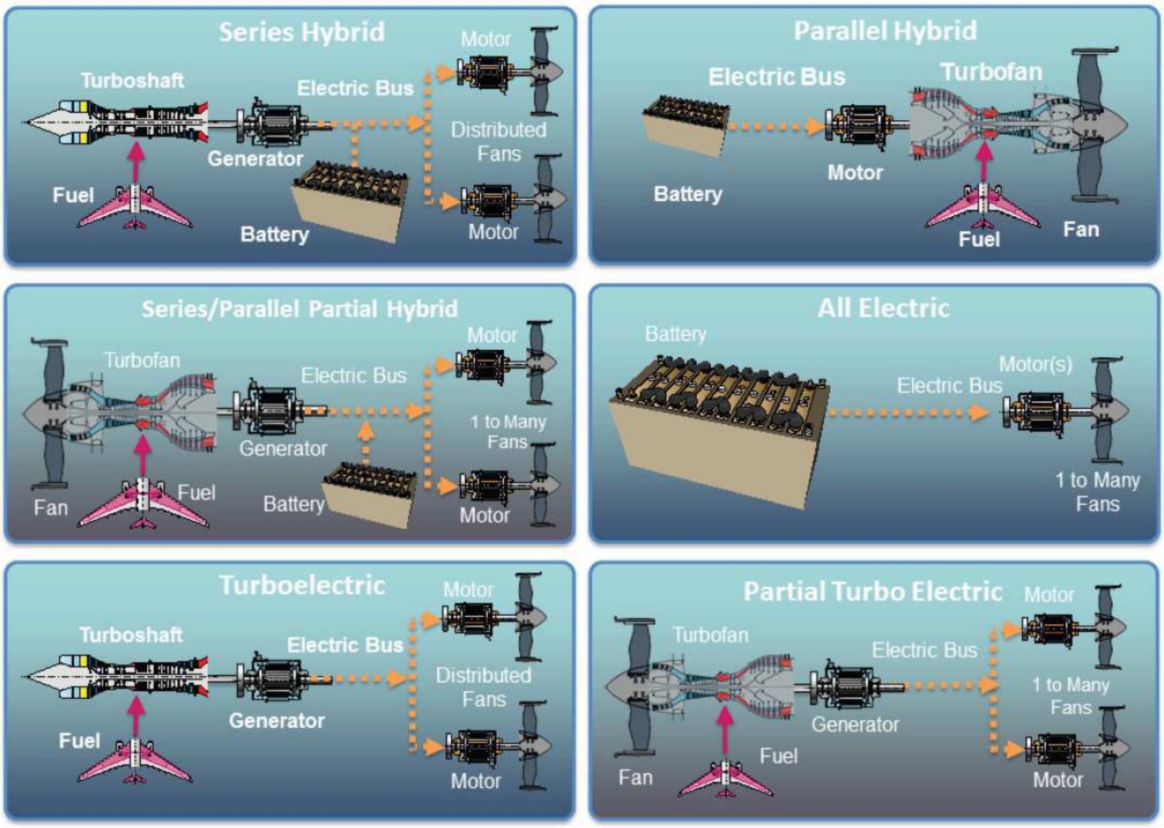


**Figure 2.1** Types of electric propulsion (NAP 2016)

The all-electric systems use batteries as the only source of power propulsion. The hybrid electric systems use a combination of gas engines and batteries. The gas turbine is the main source of propulsion, and it also charges the batteries when it is possible. This batteries are used to provide energy in the flight phases required. With the parallel hybrid system, the batteries and the turbine are mounted in the same shaft, so both of either can provide the propulsion. With the series hybrid system, only the electric motors are mechanically connected to the fans; the gas turbine is used to drive an electrical generator, the output of which drives the motors and or charges the batteries. The series/parallel partial hybrid system consist in one or more fans that can be driven directly by a gas turbine as well as other fans that are driven exclusively by electrical motors; these motors can be powered by a battery or by a turbine-driven generator. Regarding the turboelectric propulsion, it does not rely in batteries for propulsion energy during any phase of flight. The full turboelectric propulsion uses a turboshaft to drive electric generators, which power inverters and eventually individual direct current motors that drive the individual distributed electric fans. The partial turboelectric substitutes the turboshaft for a gas turbine. Then, part of the propulsion is provided by electric energy, and the rest is provided by a gas turbine.

To compare the electrical propulsion with the combustion propulsion, it is necessary to talk about the storage energy and weight. While batteries can be used as energy stores, their efficiency compared with fuel is appalling. As example, 1 kg of Jet fuel stores near 60 times as much energy as the best current battery using Lithium-Ion technology. If one compare space efficiency, one liter of jet fuel stores 20 times as much energy as one liter of Lithium-Ion battery. But the problem in the aircraft industry is not related to the space, but to the weight. In terms of weight, a kilogram of jet fuel stores 11.900 Wh of energy, meanwhile a kilogram of Lithium-Ion battery stores 200 Wh of energy.

The next step is to take into account the efficiency during the transformation of this storage energy in movement. A modern gas turbine core has an efficiency of transferring Jet fuel energy into shaft work of around 55%. The most modern electrical motor has an efficiency of 95%. Add to that a power converter (called an inverter) from battery DC power to electrical motor AC power of 90% efficiency. Putting all the information together in Table 2.1.

**Table 2.1** Values of power given to the shaft per kilogram.

| | Storage energy (Wh/kg) | Global efficiency | Shaft power (W/kg) |
|---|---|---|---|
| Jet fuel | 11900 | 0.55 | 6545 |
| Battery | 200 | $0.95 \cdot 0.90 = 0.86$ | 172 |

To make another comparison, it can be placed in a chart the mass energy density versus the volume energy density of every fuel. The ideal fuel for the aircraft industry should be one with high mass energy density but also high volumetric energy density. For the referred case, it can be seen in Figure 2.2 the differences between Li-Ion battery and Kerosene. With the development of the technology, it maybe could be possible to displace the Li-Ion battery to a more competitive position. It also could be possible the development of new kind of batteries, with better features. Other way of propulsion could be the liquid hydrogen, possibility not included in this report.

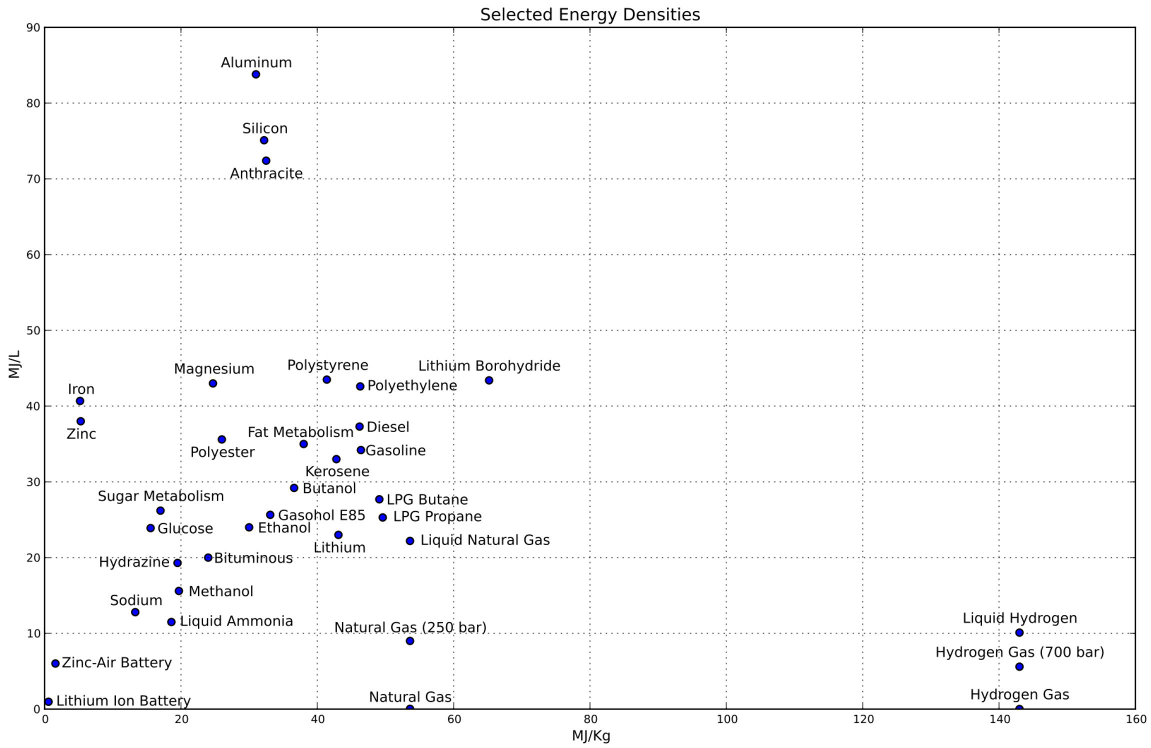


**Figure 2.2** Mass energy density vs. volume energy density (Yin 2016)

The all-electric long commercial flights are not possible with the current technology. It will remain like this until more efficient battery technology has come onto the market. All-electric battery powered airplane configurations is then limited to short range flights (UAVs and UAT). The hybrid electric propulsion and turboelectric propulsion are then the possibilities for short and medium commercial aircraft.

## 2.2 Current Electrical Aircraft Projects

Nowadays, so many different electrical projects in aviation are being developed. It is believed that this kind of aviation is going to be the future of the aviation. That is the reason why there is so much hope in having good results, and the reason why every company developing this kind of projects are selling themselves as the future alternative to fly. The German consultancy *Roland Berger* says that almost 170 electrically powered aircraft programs are currently in development, with the total set to surpass 200 by the end of the year 2019 (Sarsfield 2019). The number of electrical programs has increased a 50% since April 2018. The Urban Air Taxi market is the sector with more projects, accounting for half of all the projects recorded. Regarding the geographical distribution, Europe has the largest number of programs, with 72 in development, followed by USA with 67.

The current projects in electrical aviation focus on 4 different areas: general aviation, UAT, regional aircraft and large commercial aircraft. In this master thesis, a several projects related to the UAT and the regional aircraft are going to be mentioned and briefly analyzed.

### 2.2.1 Urban Air Taxi

The UAT seeks to solve the problems of the megacities mobility with the air travel in urban environments. The avoidance of the traffic jam is the main advantage of the UAT. The autonomy of this kind of aircraft is maybe not so long, but with the cruise speed around 80 km/h and 120 km/h, it means that for an average flight of 20 minutes, the distance covered is between 26 km and 36 km. This distance is enough to cover the longest trip of the biggest cities in the world, as Figure 2.3 shows. The mission of the UAT is to transport passengers and luggage from one point to another point within a defined urban metropolitan area. In order to accomplish this mission, the Electrical Vertical Take Off and Landing will need to address so many requirements. First off all are the safety requirements. EASA is currently working in this area, to provide the requirements needed by the EVTOL (EASA 2019). The noise emission is another issue, due to the UAT are going to fly over the cities. The range and speed shall be enough to cover the distances of the cities in a reasonable amount of time but also without generating high levels of noise. Regarding the operating costs, the cost of the energy and batteries will contribute the most to the final result. But some different factors with an unknown impact can modify this result: maintenance, taxes, amortization... The number of passengers seats is also a key design driver. They will size the price of the trip, because the passengers are the only possible income. The passengers will need to be able to embark, travel and disembark comfortably and safety, so the UAT have to be design for usability too.

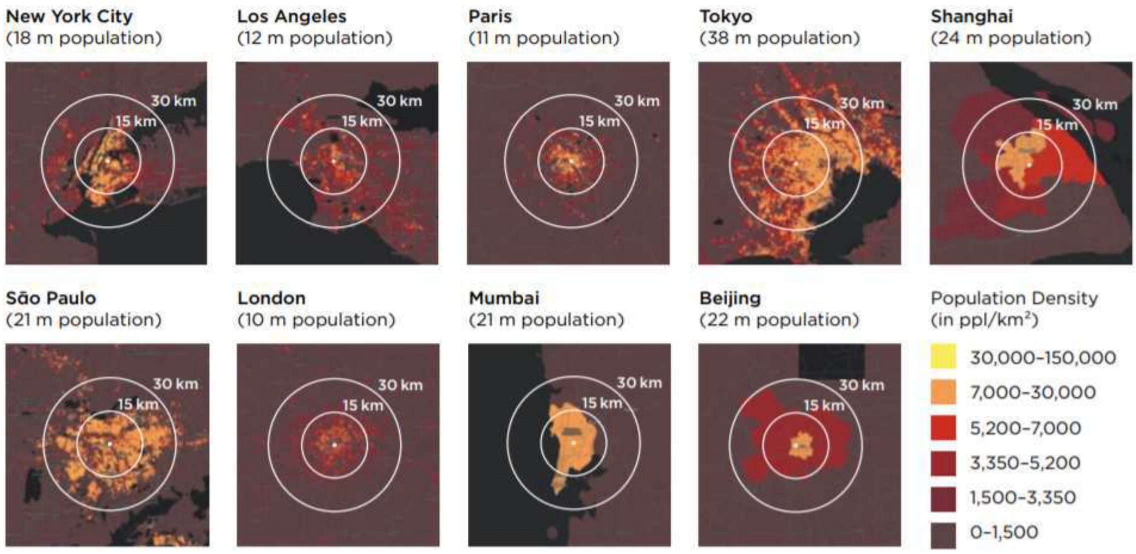


**Figure 2.3** Urban area of the largest city in the World (Volocopter 2019)

One of the current projects in development is the *2X*, by the *Volocopter* company (Figure 2.4) . The project aims to bring an UAT into the market. The *Volocopter* company says that this UAT will have capacity for one passenger and one crew. It will work thanks to the performance of 18 electric motors with only one degree of freedom: the revolutions per minute. The simplicity together with the large number of engines will ensure the safety of the operations. Also the characteristics of this engines will be such that the noise emission will be within reasonable limits. Regarding the performance of the *2X*, it will fly at a maximum speed of 100 km/h, with a range of 27 km with an average speed of 70 km/h, and an endurance of the batteries of 30 minutes. The design of the *2X* is optimized to change the batteries for every flight, which means it is required to have the necessary infrastructure in the places where it will operate. This will enlarge the life of the batteries and reduce the costs in long term.


**Figure 2.4** *2X* design (Volocopter 2019)

Another project in development is the *CityAirbus*, by *AIRBUS* (Figure 2.5). This project is an electrically powered EVTOL aircraft demonstrator, so it aims to settle the base for the future UAT. To avoid ground traffic congestion, *AIRBUS* propose an all electrical four seat UAT. One pilot will be required to transport the passengers. The 8 electric ducted fan fed by 8 electrical motors of 100 kW each one will make the *CityAirbus* fly. The four batteries with a capacity of 110 kW for each battery makes a total amount of 110 kWh. This makes the maximum autonomy of the UAT to be 15 minutes, with a cruise speed of 120 km/h.

This two projects are some examples of all the projects that are currently being developed. All these projects aim to serve the same market with similar characteristics. But analyzing more in depth these projects, several questions arises. First question is about the capacity of the UAT. Only one passenger with one crew for the *2X*, and four passengers with one crew for the *CityAirbus*. All the incomes, expenses, emissions and pollution only can be deducted to a few number of passengers. The UATs must have then a really high efficiency in every single area in order to reduce the cost as much as possible. With the development of the technology, maybe the crew can be substituted by an autonomous pilot. Then all the performance of the UAT can be deducted to more passengers, but the requirements in safety will be so demanding, and the

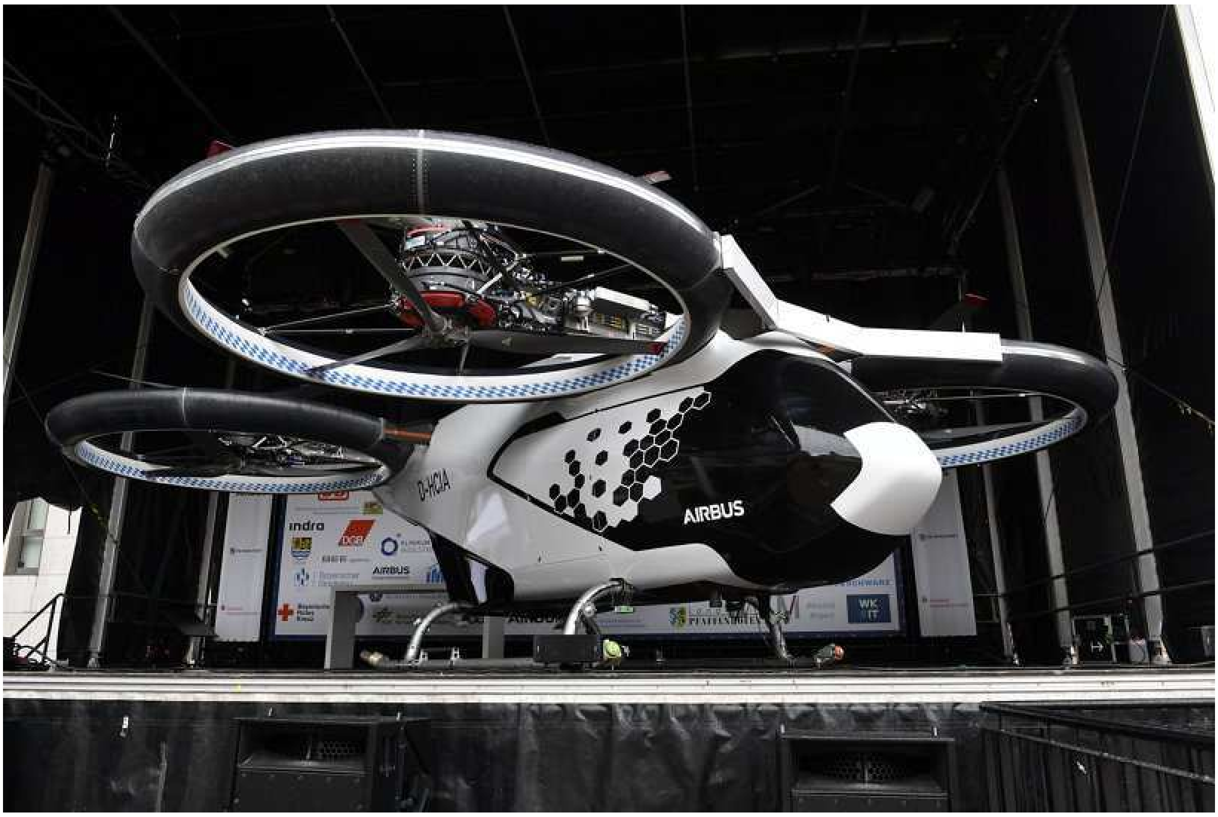


**Figure 2.5** *CityAirbus* design (Airbus 2019)

investment to develop this autonomous pilot will be very large, making everything even more expensive. This safety in the *2X* its claim to be achieved due to the simplicity of the design. Simply airframe, with a simply performance of the engines, and a high number of engines to ensure redundancy. This makes the design stage a key factor in this project. Time and money is required to develop a good and efficient design. Safety is also related to collision avoidance, and bird strike damage. It is reasonable to assume that other aircraft and UAVs will be operating in the same airspace, together with the presence of birds. This will affect to the autonomy and speed of the UAT. Due to the autonomy is not really high for both projects, many places for doing the vertical landing and take off will be required, as alternative places to land. It is necessary to develop then the infrastructure for this kind of aviation. Regarding the noise, *Volocopter* bases on the idea that low disc loading and low rotor tip speed produce less noise than those with higher disc loading and faster rotor tip speeds. The rotor tip speed and number of rotor blades defines the frequency signature and in combination with the disc loading defines the overall noise level of the rotor. This idea must be truth if the *2X* wants to have a not high noise emissions. The *CityAirbus* wants to achieve this noise reduction only with the performance of the ducted fans. Regardless the way the noise reduction is achieved, the noise emitted is a key factor to the success of this kind of aviation. High levels of noise are not going to be accepted by the certification authorities neither the population.

Moving to the operating costs, some points needs to be discussed. The viability of this alternative way of transport depends largely in the final price of the product. The main cost comes from the use of the batteries. For every flight these batteries need to be replaced for another recharged batteries. So in every place designed to pick up and leave the passengers, recharged batteries are required to replace the wasted batteries. It is desired then to enlarge the life of these batteries, in order to amortize them. To enlarge the battery life, it is required to recharge it slowly, because fast recharges reduces the battery life. All of this leads to the necessity of develop the infrastructure necessary to not only pick up and leave the passengers but also to recharge, store and replace the batteries. In order to amortize the batteries and also the UAT itself, it would be necessary to have a high number of flights per day. The average time of one trip is between 15 minutes and 40 minutes, so maybe between 20 flights per day and 30 days per flight would be possible. But the higher the number of flights, the higher number of batteries required, because, as mentioned before, they need to be recharged slowly. It will be required then to study how many batteries are required for a single UAT, and how many UATs are going to work in the same heliport. This two facts together will size not only the amount of batteries required but also the amount of slots necessary for recharging the batteries in every heliport.

As final point, it is necessary to mention the emissions of this kind of transport. Being a battery powered vehicle generates the main advantage of having zero emissions, if this electricity comes from a clean source of energy. But here is necessary to talk not only about the origin of the energy but also about the management of this energy. Using the data given in Volocopter (2019), a typical EVTOL design have a power requirement ranging from 500 kW to 1000 kW for take off and landing. If it is assumed three minutes for take off and landing per flight, this results in energy consumption of 25 kWh to 50 kWh just for take off and landing. This is equivalent to the full battery charge of an electric car, and it is consumed in just three minutes. Taking as an example for an electrical car the the *Tesla 3*, and taking a generic UAT with 2 passengers and a range of 30 km, the comparison of the kWh per passenger and kilometer is shown in Table 2.2. It can be seen that the passenger of a UAT would require ten times more energy per kilometer than a passenger of a electrical car. And this result only take into account the take off and landing flight phases, not the cruise phase. This result wants to show that the energy can come from a clean source, making the UAT a zero emission vehicle, but the management of the energy is also important. Because this result not only affects then environmental area, it also have repercussion in the economic area. A ticket of the UAT shall be ten times more expensive than the ticket of an electrical taxi only to cover the cost of the energy. Tickets ten times more expensive are not going to be affordable for every customer.

**Table 2.2** Different kWh per passenger and km for a generic UAT and a *Tesla 3*

| | Energy (kWh) | Passengers | Range (km) | kWh per passenger and km |
|---|---|---|---|---|
| Generic UAT | 25 - 50 | 2 | 30 | 0.417 - 0.833 |
| Tesla 3 | 50 | 5 | 350 | 0.0286 |

It is true that, nowadays, the megacities are getting more and more congested. Thus, it is critical to develop alternative solutions to fix this situation. The use of means of transport which moves through the air can be a solution. But, with all this features, and with the current technology, it seems that it would be necessary to wait until this sort of transport become more accessible to everyone, and more feasible. This means that it is necessary to invest in this kind of projects, but it is also necessary to be critical and objective with the results.

### 2.2.2 Regional Aircraft

The fully electrical large commercial flights are not possible nowadays. With the development of the technology, maybe in the future large commercial electrical flights are feasible. But it is possible to use aircraft full electric and partially electric for short and medium range. The degree of electric propulsion achieved by these aircraft depends mostly on the technology used in each project. The main problem for the success of the electrical aircraft is related to the first law of aircraft design.

$$m_{MTO} = m_{PL} + m_F + m_{OE} \quad , \quad m_{MTO} = \frac{m_{PL}}{1 - \dfrac{m_F}{m_{MTO}} - \dfrac{m_{OE}}{m_{MTO}}} \tag{2.1}$$

The $m_{MTO}$ is directly proportional to the $m_{PL}$, and this relation depends on the $m_F/m_{MTO}$ and $m_{OE}/m_{MTO}$ ratio. The value of the ratio $m_{OE}/m_{MTO}$ is normally around 0.5. The ratio $m_F/m_{MTO}$ is then fixed in a range from more than 0 to less than 0.5. These limits represent two non possible situations: no possible flight because there is no fuel for the 0 ratio, and no possible flight because $m_{MTO}$ would be infinite for the 0.5 ratio. The problem in the electrical aviation comes from the value of $m_F/m_{MTO}$ ratio it has got. Looking at Table 2.1, it can be appreciated that the jet fuel produces 60 times more power than a battery for the same weight. This means that, for the same flight and same aircraft, a electrical flight only with batteries would require a higher ratio of $m_F/m_{MTO}$ than a conventional aircraft, because for the electrical aircraft, the battery weight is the $m_F$. Maybe the flight is possible, increasing the value of the $m_{MTO}$, which will reduce the $m_F/m_{MTO}$ ratio, but then the $m_{MTO}$ would be too large for a few number of passengers. For the hybrid electrical, the total $m_F$ is the sum of the fuel and the batteries, so the problem is the same than the fully electrical aircraft. The turboelectric and partial turboelectric flights have no batteries, so the $m_F$ is only the weight of the fuel. But here the problem is the increase on $m_{OE}$ that this new architecture supposes. The turboshaft needs for a correct performance the presence of a converter and an electrical engine. This means that the turbojet is replaced by a turboshaft, generator and electrical engine. And this four elements weight the same. So one weight is being replaced by three weights. Adding weight that is not PL weight is not worthy in aviation.

The first project that is going to be mentioned is the *Project 804* by the *United Technologies* company. This project consists in the installation of a partial electric propulsion demonstration system on a modified *Bombardier Dash 8-100*. One engine will be replaced for an electrical engine, and the other engine will remain the same. The main function of the electric motor is to support the turboprop engine. During take off and climb, both engines will provide half of the power to the same gearbox, which moves the propeller. *United Technologies* says that this new configuration allows the use of a smaller gas turbine engine optimized for the cruise efficiency. In this way, the overall system could deliver fuel savings up to 30%. The main save in fuel will come then from the use of the latest gas turbine technology, rather than from the use of electrical propulsion. The installation of the hybrid electric system will increase the OEW and halve the aircraft fuel capacity, leading to a reduction in range from 1000 NM to 600 NM in order to carry the same number of passengers. *United Technologies* dismisses a full electric architecture, because with the current technology, the weight of the batteries would exceed the MTOW. The main goal of this project is to deliver technology that could be used for platforms ranging from general aviation to large commercial jets, and to accelerate the development of suitable batteries, electric motors and power managements systems. With this few numbers given by the company, the following calculation can be realize. The total amount of fuel save is 30%, but the reduction in range is $(600-1000)/1000$ % $= -40\%$. This means that for the new aircraft, the fuel consumed per kilometer is $(0.7/600-1/1000)/(1/1000)$ % $= 16.67\%$ more. The aircraft will carry the same number of passengers, so the emission per passengers is going to increase, due to the fuel consumed per kilometer is higher. The new aircraft will consume more fuel per kilometer and will emit more pollutants per passenger. The numbers makes the new aircraft more expensive and less eco-friendly with the different propulsion system. Right now is then possible to fly with an hybrid electric system, but this aviation is not ready yet for come into the market, and it is not ready to reduce the emissions. More investment in this area and more development of technology is required, in order to make this sort of aviation as competitive as the convetional aviation.

Another interesting project is the *ZA10* by *Zunum*, backed by *Boeing* and *JetBlue Technology Ventures* (Figure 2.6). This projects is developing a six to twelve seats hybrid electric commuter aircraft. The aircraft is designed to carry batteries in wing compartments for normal power, and use a gas turbine engine to generate electric power to extend the range of the aircraft. Despite being a design that still requires a gas turbine engine, two 500 kW generators and batteries, *Zunum* believes the acquisition cost of the aircraft can be kept below the list price of a 4500000 USD, the average price in the market for this kind of aircraft. The optimum seat layout for this aircraft is nine seats, because only one pilot is required for the flight. This will reduce the operating costs. The key factor in this project is the specific energy of the batteries. The higher the value, the higher the maximum possible range achievable only with batteries. As soon as the energy of the batteries is over, it is required to change and feed the gas turbine with the turboshaft, burning fuel. So only one certain range of the flight is going to be covered by batteries, and the remaining range will be covered by the turboshaft.

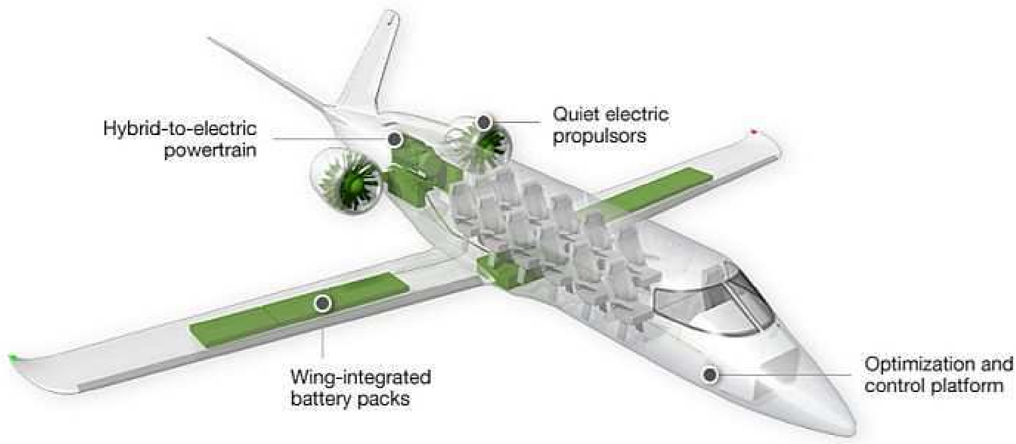


**Figure 2.6** *ZA 10* design (OGP 2018)

One first estimation of the range covered by batteries can be given for this project. Using the results shown in Scholz (2019a), this range follows the expression

$$R = \frac{m_{bat}}{m_{MTO}} \frac{1}{g} \varepsilon_{BAT} \eta_{elec} E \quad . \tag{2.2}$$

The range depends on the $m_{bat}/m_{MTO}$ ratio. To optimize the range, the specific power of the battery ($\varepsilon_{BAT}$), the efficiency of the electrical system ($\eta_{elec}$) and the glide ratio of the aircraft ($E$) shall be the higher possible. For this aircraft, the $m_{bat}$ is 1043 kg, with a $m_{MTO}$ of 5216 kg. This generates a mass ratio of $(1043/5216) = 0.199$. In order to accomplish a first estimation, the value for the specific energy is going to be set as 300 Wh/kg (a bit high value but achievable with the technology), with a efficiency of the system of 0.8 and a glide ratio of 18 (average values for this parameters). This would result, using Equation 2.2, in a range of $R = 315$ km. The range of this aircraft is 1127 km, so the distance covered only with the batteries is the 27.9% of the total. The rest of the distance flown is achieved with propulsion by fuel. Then the batteries are the device that produce the extra range, not the gas turbine. It is the opposite idea that *Zunum* sells. More than two thirds of the range is covered by the gas engine. Nevertheless, this project seems to be a good start for the electrical commercial aviation. The beginings are never easy. More information would be required to assess the environmental impact, and also the operating cost of this aircraft. With the entry of this aircraft in the market, all this questions will be answered.

The last project mentioned in this section is the *Alice* by the *Eviation Aircraft* (Figure 2.7). This aircraft is expected to be fully propelled by Lithium-Ion batteries, being in this way an electrical aircraft. The specific energy of the batteries is expected to be 260 Wh/kg (with maybe a higher value in the future), with a total weight of 3460 kg. It will fly thanks to the performance of three propellers with 260 kW of power. Two of this propellers will be placed in the wingtips, and the remaining propeller in the rear fuselage. The airframe is 95% made of composite materials, generating a MTOW of 6350 kg, and the fly-by-wire will be the way of controlling every system, making this aircraft being on the lead of aviation technology. It will have capacity for nine passengers plus two crew members, with a range of 1000 km - 1200 km and a fly height of 10000 ft. *Eviation Aircraft* assert that this new aircraft will have a direct operating cost much lower than turboprop aircraft.

With all the information given for this project, and using Equation 2.2, an estimation of the glide radio that this aircraft must have can be realized. Taking 1000 km as range, with a efficiency for the electrical layout of 0.8, the glide ratio required for this aircraft is 24. This is a high value for glide ratio in cruise, but maybe achievable by the *Alice*. Another factor that is necessary to take into account is the cruise speed. *Alice* is expected to cover the design range with a cruise velocity of 482 km/h. This is a good value for an electrical propulsion, but low compared with conventional long and medium range aviation. The time required for the flight is a factor that has influence in the economical analysis. But it also has influence in another areas such as the choice of mean of transport by the passengers. The real economic results would be visible once the aircraft entry the market. However, if this sort of aircraft succeed, it can lay the foundations for the following all electrical projects. Flying only with batteries is not easy nowadays, because of the physic properties of the batteries, and also for the economic issues compared with the conventional propulsion. Probably the overall performance of the aircraft will be more expensive than a conventional aircraft, but if it is wanted to fly green, maybe is the

**Figure 2.7** *Alice* design (Jaggi 2018)

only option. Being one of the first projects in one area is never cheap. But all the future projects from here may take advantage of all the knowledge developed for this project, making in the future the all electric aviation more affordable.

These three projects are examples of turboelectric, hybrid electric and electric projects for commercial regional aircraft. They are ambitious projects, that aims to settle the base for future projects. The first approaches to the features of this aircraft gives as result that they are going to be less competitive in the market. This have several meanings. The first meaning is that this kind of aircraft must be subsidized if they want to find a place in the market. The second meaning is that also all the current electrical projects have to be subsidized, in order to enhance the features of the aircraft, and make them more competitive. And the last meaning is that, if it is wanted nowadays to fly without the use of fuel, then it is necessary to be aware about that the ticket is going to be inevitable more expensive. The technology involved in this kind of flights is still in development.

# 3 Transformation of the Aircraft

The *E-FAN X* project consists in the replacement of one of the four *Lycoming ALF 502R-5* engine of the *BAe 146-110* for an electrical engine, becoming in this way into a hybrid aircraft. This new engine will be feed by the performance of one turboshaft plus one battery. The new engine will be placed in the same nacelle-fan configuration, the *AE3007*. This means the new external configuration will be equal to the old one, but not the internal configuration.

The *E-FAN X* will have the same external framework than the *BAe 146-110*. Then, all the parameters related to the external configuration will stay unchanged. All the dimensions of the aircraft, the drag polar, and the maximum take off weight and maximum fuel weight will be the same, among other parameters.

Regarding the internal configuration, several changes will be done. As it can be seen in Figure 3.1, a new electrical layout will be necessary. In this new scheme, the power is generated in the *AE 2100A* turboshaft, with a maximum power generation of 2.5 MW. The turboshaft is followed by the generator power electronics, which works as AC/DC converter that feeds the distribution line with a voltage of 3000 V DC. This high value of voltage will result in lighter electronics components, but supposes to face new problems, like the risk of electric arcing at high altitude, problem known as corona effect. From the generator power electronics, there is a bifurcation: one path goes to the battery, and the other path goes to the engine. The battery weight is 2000 kg with 2 MW power, and the engine works thanks to the DC/AC inverter. During the take off, turboshaft and battery will feed the engine to achieve a successful performance. During cruise, the turboshaft will feed the engine and recharge the battery.

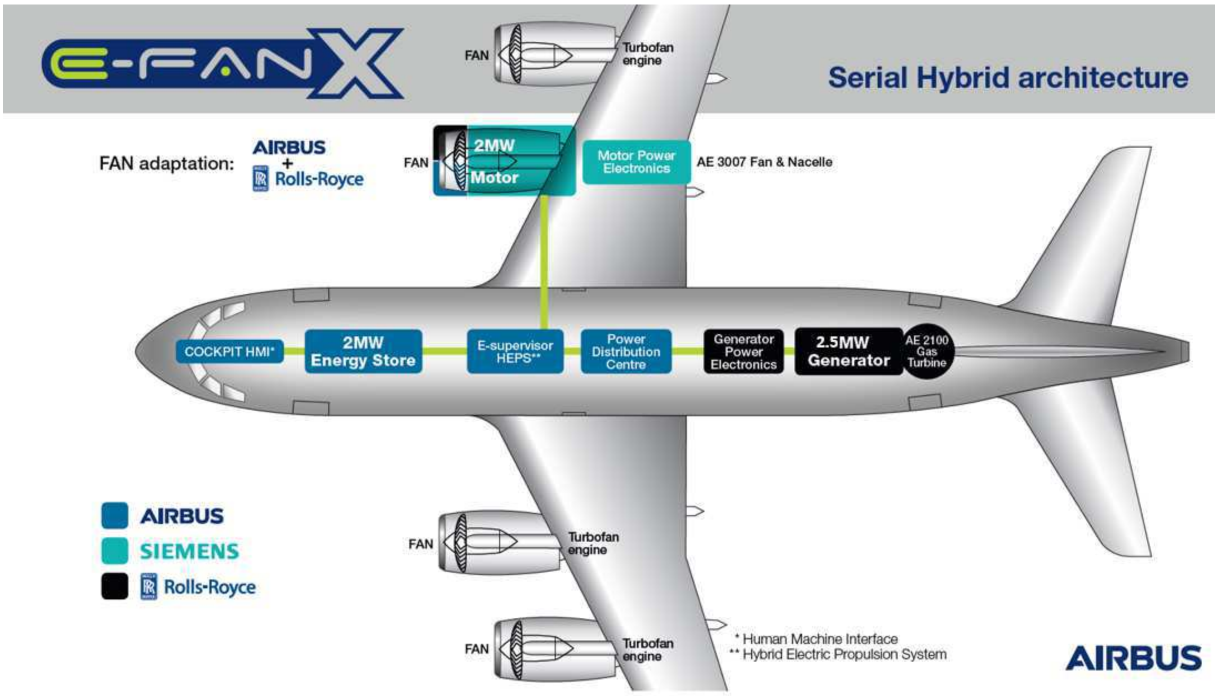


**Figure 3.1** Internal configuration of the *E-FAN X* (Bjorn 2017)

There is only one requirement for the new propulsion system: it must provide the same performance than the old propulsion system. Moreover, the aircraft performance must be the same than the old aircraft, for any flight phase. This means that the new engine must provide the same thrust for any flight phase.

In Table 3.1 it is shown the value of some important characteristics that *E-FAN X* and *BAe 146-110* share (FLIGHT 2001). In Table 3.2 it can be seen some important values of the *Lycoming ALF 502R-5*. To estimate the values of the thrust-specific fuel consumption during take off and cruise it has been used two different methods. One estimation was realized using the correlations made by Svoboda (2000). For this method it is only required to know the take off thrust, BPR and OAPR. The other estimation was done using the *OPerA* tool, developed by the *Aircraft Design and Systems Group (AERO)* of the *HAW Hamburg* (AERO 2013). This powerful tool is useful to make a preliminary design of the aircraft selected. Giving as input the known values of the aircraft selected, it can estimate the rest of the values necessary to do a complete preliminary design. Hence, the value of the two thrust-specific fuel consumption are a combination of this two methods.

**Table 3.1** Value of some parameters shared by *E-FAN X* and *BAe 146-110* (FLIGHT 2001)

| MTOW (kg) | MFV (L) | $S_w$ ($m^2$) | A | $E_{CR}$ | $M_{CR}$ | $h_{CR}$ (ft) |
|---|---|---|---|---|---|---|
| 38102 | 11728 | 77.3 | 9.5 | 16.145 | 0.7 | 35000 |

**Table 3.2** Value of some parameters of the *Lycoming ALF 502R-5*

| Weight (kg) | $T_{TO}$ (N) | BPR | OAPR | $TSFC_{TO}$ (kg/Ns) | $TSFC_{CR}$ (kg/Ns) |
|---|---|---|---|---|---|
| 606 | 31000 | 5.7 | 12.2 | $1.154 \cdot 10^{-5}$ | $2.170 \cdot 10^{-5}$ |

# 3.1 Cruise Requirements

One of the first values necessary to know is the cruise thrust, in order to size the performance of the new engine configuration. To obtain this value, is first crucial to know the value of the glide ratio during cruise. Is then unavoidable to calculate the drag polar of the *BAe 146-100*. Hence, the drag polar has been calculated, using in this master thesis the approach given by Scholz (2019b). For this method is necessary to know some parameters related to the dimensions of the wing, fuselage, horizontal tail, vertical tail, and nacelle. There are parameters that can be known directly, but there are others that need to be estimated. For this reason, a study of the *BAe 146-110* has been done, using again the *OPeRa* tool, in order to estimate the parameters that are unknown but required to calculate the drag polar (AERO 2013). Once the required values are known, the drag polar is also known at the design cruise speed.

$$C_{D,CR} = C_{D0}(V_{CR}) + \frac{C_L^2}{\pi A e(V_{CR})} = 0.0203 + \frac{C_{L,CR}^2}{\pi \cdot 9.5 \cdot 0.718} \tag{3.1}$$

It only remains to calculate $C_{L,CR}$. Using the equations for a stationary straight flight, the lift coefficient during cruise can be solved, obtaining thus the drag coefficient but also the thrust required for each engine during thrust.

$$L_{CR} = \frac{1}{2}\rho_{CR}S_w(a_{CR}M_{CR})^2C_{L,CR} = W = gm_{MTO} \tag{3.2}$$

$$D_{CR} = \frac{1}{2}\rho_{CR}S_w(a_{CR}M_{CR})^2C_{D,CR} = 4T \tag{3.3}$$

At the cruise height, the value of the density is $\rho_{CR} = 0.3795 \ \text{kg/m}^3$, and the speed sound is $a_{CR} = 296.406 \ \text{m/s}$, following the ISA rules. For Equation 3.2 has been used as cruise weight the MTOW. This supposes a conservative approach to the problem, due to during the cruise phase the real weight is lower. In this equation, is known the values of all the parameters, so the value of $C_{L,CR}$ is

$$C_{L,CR} = \frac{gm_{MTO}}{\frac{1}{2}\rho_{CR}S_w(a_{CR}M_{CR})^2} = 0.593 \tag{3.4}$$

And for the given velocity, the drag polar (Equation 3.1) gives the drag coefficient, $C_{D,CR} = 0.0367$.

Once the drag coefficient is obtained, the thrust that each engine has to give is known, solving Equation 3.3.

$$T_{CR} = \frac{\frac{1}{2}\rho_{CR}S_w(a_{CR}M_{CR})^2C_{D,CR}}{4} = 5785.818 \quad \text{N} \tag{3.5}$$

For the cruise flight of the *E-FAN X*, the new engine will have to provide the thrust given by Equation 3.5, due to no parameter involved in this calculation is going to change with the new configuration. This value of thrust is necessary in order to know the power required for this flight phase.

## 3.2 Take Off Requirements

Another important flight phase is the take off. The value of the take off thrust can be taken from the *Lycoming ALF 502R-5* data sheet, and is showed in Table 3.2. Hence, this value of thrust must be provided by the new configuration. Moreover, this flight phase size the maximum power that *AE 2100A* will have to provide. If the power required is above 2.5 MW, then the battery will have to provide the rest of the power required. More important than the possible power required by the battery, is the energy. It is necessary to know the power the battery has to provide, but also the amount of time it has to be providing that certain power. This gives the value of the energy to be recharged during cruise. It is unavoidable then to solve the take off equations, to obtain the values of time, velocity and thrust during this flight phase.

The power the turboshaft must give during the take off is

$$P(t) = \frac{T_{TO}(V_{TO})V_{TO}(t)}{\eta_{t-e}} \tag{3.6}$$

Where the efficiency of the path from the turboshaft to the engine ($\eta_{t-e}$) plays an important role. The higher the efficiency, the lower the power the turboshaft has to give. Doing an estimation about the value of the efficiency is not an easy task. One fact is that the Siemens motor and Rolls-Royce generator are non-superconducting (non-cryogenically cooled) designs. This means the power chain *AE2100A* turbine to *AE3007* fan has efficiency losses above 15% (Bjorn 2017). Taking into account that the maximum possible power developed by the *AE 2100A* is 2.5 MW and the power of the engine is 2 MW, a feasible estimation of the efficiency could be

$$\eta_{t-e} = 1 - \frac{2-2.5}{2} = 0.8 \quad . \tag{3.7}$$

The take off thrust is a function of the velocity during take off. It follows the expression, developed by Scholz (2019b).

$$\begin{aligned} \frac{T_{TO}(V_{TO})}{T_{TO}} =& 1 - \left(2.44 \cdot 10^{-4} \cdot BPR + 1.66 \cdot 10^{-3}\right) V_{TO} + \\ &+ \left(6.16 \cdot 10^{-7} \cdot BPR + 4.08 \cdot 10^{-6}\right) \cdot V_{TO}^2 \end{aligned} \tag{3.8}$$

Where the value of $T_{TO}$ is the given in Table 3.2, and represents the initial take off thrust when the aircraft is completely stopped. Once it begins to move, the take off thrust required decreases with the increase of the velocity. This equation means that once the take off velocity is known, the power required during the take off is also known. To obtain the relationship between the velocity during take off and the take off time, is crucial to solve the take off equations. This equations are two, one equation for the ground phase, and another equation for the air phase. For the ground phase equation, the aircraft goes from the initial state of no movement to the state where the velocity reaches the value that makes the normal reaction of the landing gear equal to zero. The value for this velocity is normally taken in the range of 1.1 to 1.2 times the value of the stall velocity.

$$V_{LOF} = 1.2 V_{STALL} = 1.2 \sqrt{\frac{2 g m_{MTO}}{\rho S_w C_{L,TO,x}}} = 65.611 \quad \text{m/s} \tag{3.9}$$

Where this value of lift off velocity is only valid if it is wanted to solve a take off at sea level. For a take off at higher altitude is necessary to use the corresponding value of density. The value of the maximum lift coefficient has been obtained using the *OPerA* tool, and it is equal to 2.64.

The equation that governs the ground phase follows the expression

$$\frac{dt}{dV_{T0}} = \frac{m_{MTO}}{T_{TO}(V_{TO}) - D(V_{TO}) - \mu(gm_{MTO} - L(V_{TO}))} \tag{3.10}$$

This equation need to be integrated from the initial conditions $t_i = 0, V_i = 0$ to $V_f = V_{LOF}$, to obtain the time $t = t_g$. The parameter $\mu$ corresponds to the friction coefficient. It depends on the type of surface. For a standard dry asphalt runway, this value is between 0.03-0.05. In this study a value of 0.04 has been taken into account. In this equation, the thrust, drag and lift depends on velocity. For the thrust, its value is given by Equation 3.9. For the drag and lift, their values are

$$L = \frac{1}{2}\rho S_W V_{TO}^2 C_{L,TO,X} \tag{3.11}$$

$$D = \frac{1}{2}\rho S_W V_{TO}^2 C_D(V_{TO}) = \frac{1}{2}\rho S_W V_{TO}^2 \left( C_{D0}(V_{TO}) + \frac{C_{L,TO,X}^2}{\pi A e(V_{TO})} \right) \tag{3.12}$$

For the lift equation, the value of the lift coefficient is fixed at its maximum value in take off. Regarding the drag equation, the drag coefficient depends on velocity, as both terms, induced and parasitic, depends on velocity.

To solve the complete take off performance, it has to be solved the second segment too. In this phase, the equations are

$$m_{MTO}\frac{dt}{dV_{TO}} = T_{TO}(V_{TO}) - D(V_{TO}) - gm_{MTO} sin\gamma \tag{3.13}$$

$$m_{MTO}V_{TO}\frac{d\gamma}{dV_{TO}} = L(V_{TO}) - gm_{MTO} cos\gamma \tag{3.14}$$

And the initial conditions for the integration are $t_i = t_g, V_i = V_{LOF}, \gamma_i = 0$, being the final conditions $V_f = 1.3V_{STALL} = 71.078$ m/s, $\gamma_f = 0.03$. The final values of the velocity and the gamma angle are fixed by the certification rules. Up from this situation, the thrust necessary to be provided is constant until the climb phase is over, and the cruise phase begins.

In order to solve Equations 3.11, 3.14, 3.15, a numerical integration has been developed. With this, is known the total amount of time required for the take off, and also the power required for each moment during the take off. For a sea level take off, the evolution of the velocity, thrust and power is showed in Figure 3.2. The final time to do the take off is $t_f = 26.38$ s. But the most important result here is the value of the maximum power developed by the turboshaft. It is less than 2.5 MW. No power coming from the battery is necessary. The performance of the turboshaft is enough to do a successful take off. This supposes a dilemma. The information about this project is limited, but it has been claimed that the *E-FAN X* will have a battery on

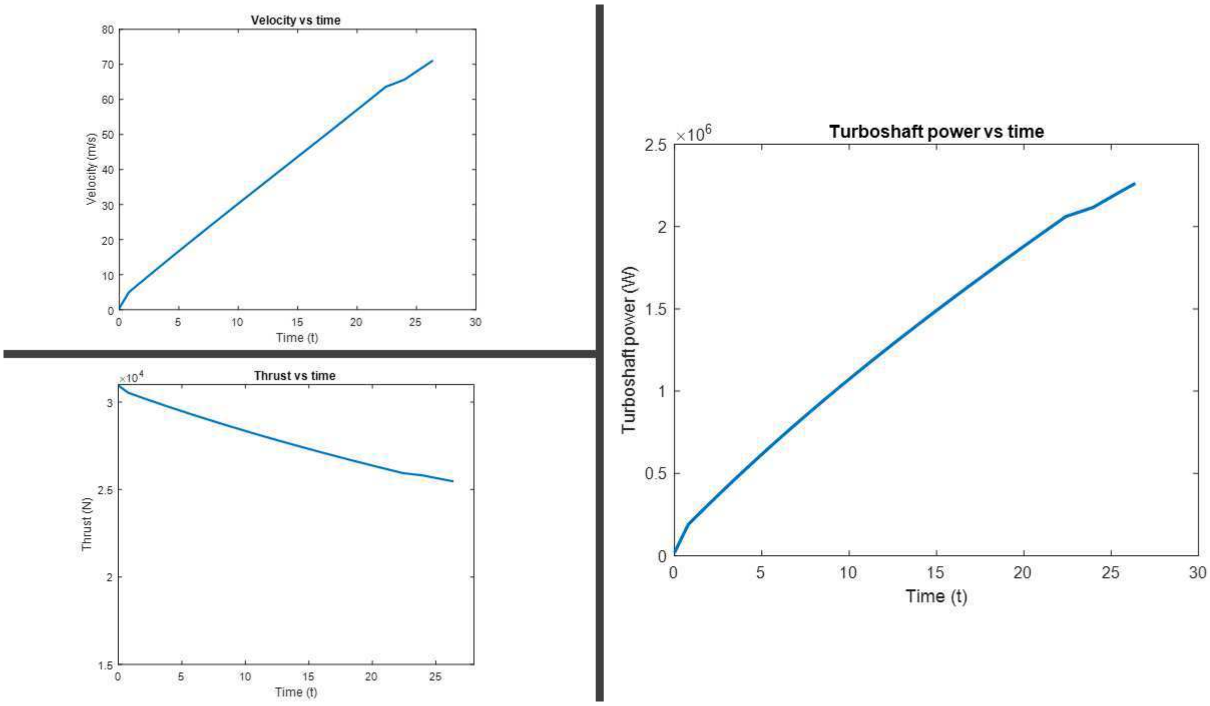


**Figure 3.2** Values of velocity, thrust and power for a sea level take off

board because it is necessary for the take off and climbing phases. But in this master thesis it has been demonstrated that no battery is necessary for the take off and climbing phases for a sea level take off. In fact, a successful take off can be done until a height of 2000 m, as it shows Figure 3.3.

The presence of the battery would mean that the value of the new OEW plus FW would be higher for the same MTOW. This increase in weight would be compensated with the reduction in fuel consumed. But as it is explained in the following section, this reduction in fuel consumed is not enough to cover the 2 tons battery weight. The weight reduction must be achieved in other way. With more weight due to the battery, and a slightly reduction in fuel consumed, the total increase in weight must be mitigated with the reduction in the number of passengers, in order to have the same MTOW. This fact is not good for the economic and environmental evaluation (see Chapter 4 and Chapter 5), because a reduction in the number of seats increase the ratio per seat of every evaluation. For this reason, the study that has been done from here is with the configuration without the battery (Figure 3.4). The only objective of the battery was to give support during take off and climbing phases. Once it has been demonstrated that it is not necessary for its only supposed requirement, it would make no sense keep using the configuration with the battery inboard. The fact of removing the battery from the final configuration supposes an unexpected discovery, and a big step of this master thesis.

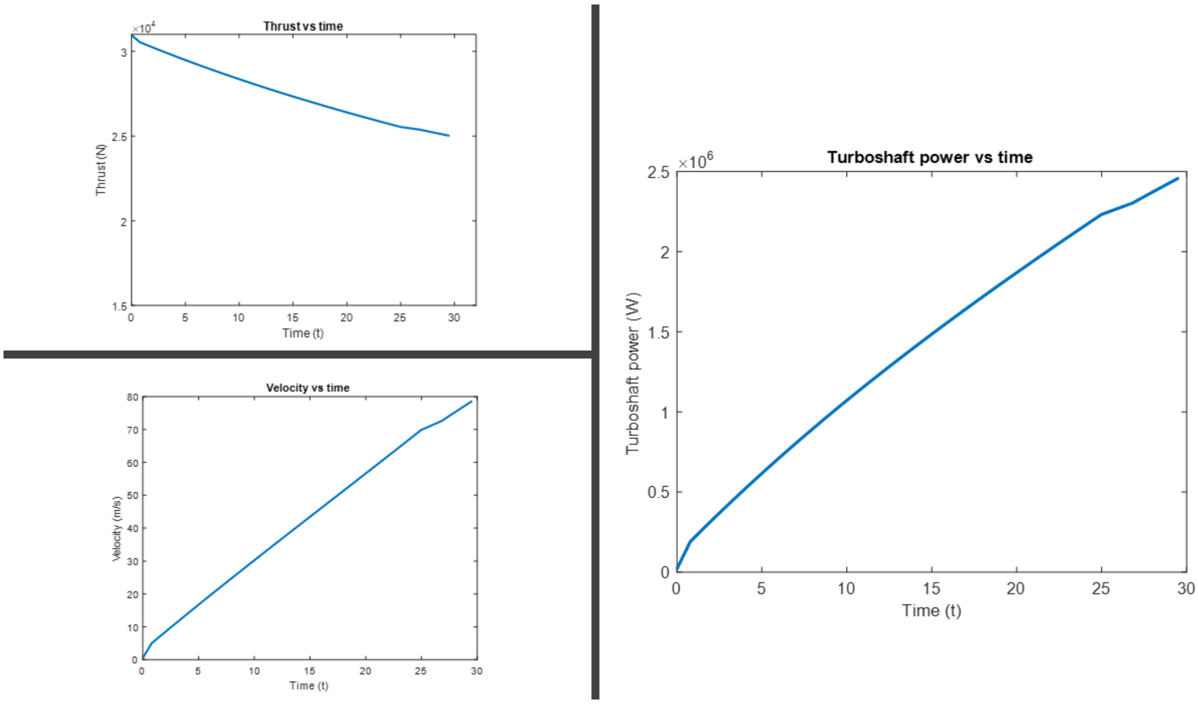


**Figure 3.3** Values of velocity, thrust and power for a 2000m height take off

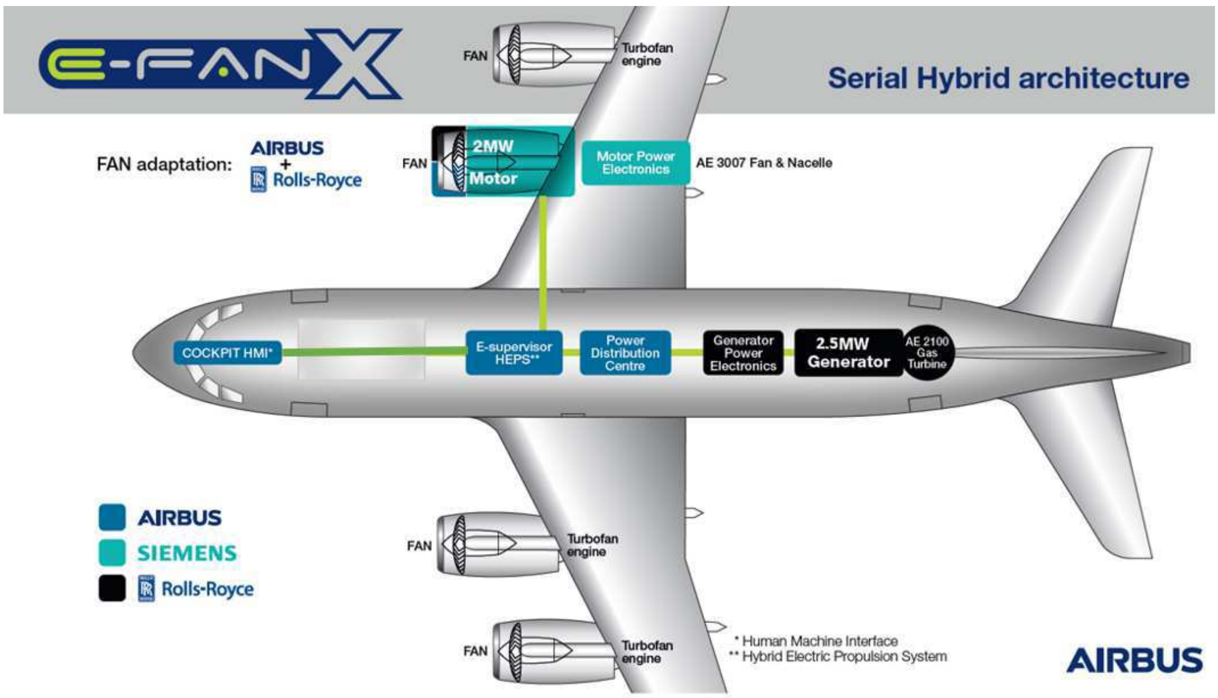


**Figure 3.4** Scheme of the final configuration without battery (based on Bjorn 2017)

## 3.3 New Engine Performance

The fact that no battery is required changes completely the performance of the *AE 2100A* turboshaft. Now it does not have to feed the battery during cruise, which means less fuel consumption. Few data is known about the features of this engine. Some of this known values are shown in Table 3.3.

**Table 3.3** Value of some parameters of the *AE 2100A*

| Weight (kg) | Max. Power (MW) | OAPR | Price (USD) |
|---|---|---|---|
| 730 | 2.5 | 17 | 3100000 |

Two values that are crucial to know are the power specific fuel consumption during cruise and take off. One way to obtain these values is using the method developed by Koppe (2012). In this bachelor project, the author developed a equation that gives the power specific fuel consumption of the turboshaft just knowing the values of the power required, the OAPR and the exit turbine temperature. The OAPR is a known value, the power required depends on the flight phase, and the exit turbine temperature is unknown. The equation that relates all this variables is

$$PSFC = 3.25369 \cdot 10^{-7} - 1.00060 \cdot 10^{-8} \cdot ln(P \cdot OAPR \cdot T_{4t}) \quad \text{kg/Ws} \tag{3.15}$$

The exit turbine temperature is unknown, but can be delimited in the range of 1350 K to 1500 K. Despite this value has influence on Equation 3.15, this influence is not as strong as the value of the power, as it can be seen in Table 3.4. The variation of the temperature between the two limits imposed, with a fixed value of power, generates a difference in the PSFC in the first decimal position. In contrast, a change in the power with a fixed value of temperature generates a difference in the unit position. The value of the power has more influence, and for this reason, the exact value of the turbine exit temperature is not completely necessary. From this point, every value of the PSFC showed in this master thesis has been obtained doing the average of the values of the PSFC for each value of temperature from 1350 K to 1500 K.

**Table 3.4** Variation of the PSFC with the exit turbine temperature and power

| Temperature (K) | Power (MW) | OAPR | PSFC (kg/Ws) |
|---|---|---|---|
| 1350 | 2.5 | 17 | $7.734 \cdot 10^{-8}$ |
| 1500 | 2.5 | 17 | $7.630 \cdot 10^{-8}$ |
| 1350 | 1 | 17 | $8.650 \cdot 10^{-8}$ |
| 1500 | 1 | 17 | $8.545 \cdot 10^{-8}$ |

The estimation of the value of the PSFC during the cruise phase is not difficult, due to the thrust in this flight phase is fixed, and then the power. Taking into account the thrust required for the cruise (Equation 3.5), the cruise speed and height (Table 3.1), and the efficiency of the electrical system (Equation 3.7), and following the assumption that the exit turbine temperature is between 1350 K and 1500 K, the result is, using Equation 3.15

$$P_{CR} = \frac{T_{CR} M_{CR} a_{CR}}{\eta_{t-e}} = 1500582 \quad \text{W} \tag{3.16}$$

$$PSFC_{CR,1,AE}(1500582\ \text{W}, 1350\ \ \text{K}, 17) = 8.260 \cdot 10^{-8} \quad \text{kg/Ws} \tag{3.17}$$

$$PSFC_{CR,1,AE}(1500582\ \text{W}, 1500\ \ \text{K}, 17) = 8.154 \cdot 10^{-8} \quad \text{kg/Ws} \tag{3.18}$$

$$PSFC_{CR,AE} = \frac{PSFC_{CR,1} + PSFC_{CR,2}}{2} = 8.207 \cdot 10^{-8} \quad \text{kg/Ws} \tag{3.19}$$

During the take off, the power goes from zero to the value required for take off. The PSFC is continuously changing during the take off, increasing as the power required increased. If one value is required, a good approximation could be an average of all the values that occurs in this flight phase. The power required at any moment is known, once the equations of take off have been solved (Equations 3.11, 3.14 and 3.15). With this, and the assumption about the exit turbine temperature, the value of the power specific fuel consumption during take off is

$$PSFC_{TO,AE} = 1.490 \cdot 10^{-7} \quad \text{kg/Ws} \quad . \tag{3.20}$$

With this two values, more features of the *AE 2100A* are known. But it is not possible to do a comparison between the *AE 2100A* and the *Lycoming ALF 502R-5*, due the first engine works in terms of power, and the second engine works in terms of thrust. Taking a look at the units of the PSFC and TSFC, it can be seen that they only differ in one physic magnitude: if the PSFC is multplied by a characteristic velocity, it would have the same units as the TSFC.

$$[TSFC] = \left[\frac{\text{kg}}{\text{Ns}}\right] = \left[\frac{\text{kg}}{\text{kg}\frac{\text{m}}{\text{s}^2}\text{s}}\right] = \left[\frac{\text{s}}{\text{m}}\right] \tag{3.21}$$

$$[PSFC] = \left[\frac{\text{kg}}{\text{Ws}}\right] = \left[\frac{\text{kg}}{\text{N}\frac{\text{m}}{\text{s}}\text{s}}\right] = \left[\frac{\text{kg}}{\text{kg}\frac{\text{m}}{\text{s}^2}\text{m}}\right] = \left[\frac{\text{s}^2}{\text{m}^2}\right] \tag{3.22}$$

Then, it can be obtained the equivalent TSFC for the *AE 2100A*. It is only necessary to multiply the PSFC for a characteristic velocity. During cruise, this characteristic velocity is the ratio between the power necessary for the cruise and the corresponding thrust generated. This ratio has units of velocity. The equivalent TSFC for the *AE 2100A* would be then

$$[TSFC_{CR,AE}] = \left[PSFC_{CR,AE}\frac{P_{CR}}{T_{CR}}\right] \tag{3.23}$$

$$TSFC_{CR,AE} = 2.128 \cdot 10^{-5} \quad \text{kg/Ns} \tag{3.24}$$

Due to the efficiency of the electrical system, the characteristic velocity is $P_{CR}/T_{CR} = 259.355$ m/s. This value is higher than 207.484 m/s, the value of the cruise speed at that altitude. Whit a efficiency of one, Equation 3.17 would provide a lower value of power, and the characteristic velocity would correspond to the cruise velocity. This would generate a lower TSFC. This means that the efficiency of the electrical system plays a fundamental role.

To obtain the TSFC during take off, the same idea has been followed, but applied in a different way, due to the different characteristics between cruise and take off. The average TSFC during take off is then

$$TSFC_{TO,AE} = 7.318 \cdot 10^{-6} \quad \text{kg/Ns} \tag{3.25}$$

Now it is possible to do a comparison related to the fuel consumption between the *AE 2100A* and the *Lycoming ALF 502R-5*, as it shows Table 3.5

**Table 3.5** Differences between the performance of the *AE 2100A* and the *ALF 502R-5*

| TSFC (kg/Ns) | *AE 2100A* | *Lycoming ALF 502R-5* | Percentage difference |
|---|---|---|---|
| Cruise | $2.128 \cdot 10^{-5}$ | $2.170 \cdot 10^{-5}$ | -1.935% |
| Take off | $7.318 \cdot 10^{-6}$ | $1.154 \cdot 10^{-5}$ | - 36.59% |

But it is also possible now to do a comparison between the different fuel consumption of the old configuration (four *Lycoming ALF 502R-5*) and the new configuration (three *Lycoming ALF 502R-5* and one *AE 2100A*). It is only required to calculate the new TSFC during cruise and take off, calculus done taking into account that now there are three old engines and one new engine.

$$TSFC_{CR,N} = \frac{3}{4}TSFC_{CR,ALF} + \frac{1}{4}TSFC_{CR,AE} = 2.159 \cdot 10^{-5} \quad \text{kg/Ns} \tag{3.26}$$

$$TSFC_{TO,N} = \frac{3}{4}TSFC_{TO,ALF} + \frac{1}{4}TSFC_{TO,AE} = 1.048 \cdot 10^{-5} \quad \text{kg/Ns} \tag{3.27}$$

As the cruise flight phase is the main phase of every flight (the phase that takes more time), it can be seen that the replacement of only one engine does not have a big impact on the overall

**Table 3.6** Differences between the performance of the new and old configuration

| TSFC (kg/Ns) | New configuration | Old configuration | Percentage difference |
|---|---|---|---|
| Cruise | $2.159 \cdot 10^{-5}$ | $2.170 \cdot 10^{-5}$ | -0.506% |
| Take off | $1.048 \cdot 10^{-5}$ | $1.154 \cdot 10^{-5}$ | -9.146% |

performance (Table 3.6). Only a reduction of 0.535% is achieved with the new configuration. It is true that during the take off the total reduction has a significant value, but this phase flight is very short in time. The reduction would be higher with the replacement of more than one engine, and with a higher value of the efficiency of the path form the turboshaft to the engine. Just as example, in Table 3.7 is shown the different values of the equivalent TSFC of the new engine with the different values of the efficiency. The higher the efficiency, the lower the equivalent TSFC. This leaves an open door for the future technology. If the technology would be able to develop a system with a high efficiency, then the save in fuel will be significant. This could be the future of the aeronautic sector.

**Table 3.7** Value of the $TSFC_{CR}$ for the *E-FAN X* with different $\eta_{T-E}$

| $\eta_{T-E}$ | $P_{CR}$ (W) | PSFC (kg/Ws) | TSFC (kg/Ns) | Percentage difference with one old engine |
|---|---|---|---|---|
| 0.85 | 1412313 | $8.268 \cdot 10^{-8}$ | $2.018 \cdot 10^{-5}$ | -6.995% |
| 0.9 | 1333851 | $8.325 \cdot 10^{-8}$ | $1.919 \cdot 10^{-5}$ | -11.556% |
| 0.95 | 1263648 | $8.379 \cdot 10^{-8}$ | $1.830 \cdot 10^{-5}$ | -15.666% |

It has to be noticed that all the calculus in this section has been done without the presence of the battery. If the battery were necessary during take off, it would mean that during the cruise phase the turboshaft would have to develop even more power, at least until the battery is fully recharged. During this recharging time, the value of the TSFC would be higher, because the value of the power generated would be higher for the same value of thrust (Equation 3.23). The presence of the battery would save fuel during the take off, but not during the whole cruise. During the time the battery is being recharged, the fuel consumption would be higher. During the time the battery is fully recharged, the fuel consumption would be lower. In this situation, the recharging time would size the amount of fuel saved. Depending on the performance of the turboshaft, the battery, and the features of the electric layout, the reduction in fuel consumption would be higher or lower. For the calculations made here, the difference in fuel consumption between the new and old configuration are narrow. With the presence of the battery, it is not clear what would happen, if the fuel consumption of the new engine would be lower or not compared to the old engines. The necessity of the battery for the real final configuration of the *E-FAN X* is again in doubt.

## 3.4 *E-FAN X* Operative Empty Weight

During the transformation, the aircraft will have one *Lycoming ALF 502R-5* engine less, but will have to incorporate the *AE 2100A*, the DC converter and the *Siemens* engine, in addition to the new cable layout required for this configuration. Due to the MTOW is the same, this increase of

OEW will mean an inevitable decrease of the MPL. In order to size the new number of seats, it is first necessary to know the new OEW. The weights of the *Lycoming ALF 502R-5* and *AE 2100A* are known, but not the weights of the converter and the *Siemens* engine. For the converter, the experience says that a normal weight for converters of this characteristics is between 400 kg and 700 kg. With the assumption that this project uses the newest technology, in this master thesis a weight of 400 kg has been taken into account. Regarding the *Siemens* engine, a power mass ratio higher than 5.2 kW/kg is expected (Bjorn 2017). If the maximum power that the engine has to develop is 2 MW, with a power mass ratio of 6 (higher than the 5.2 expected), the weight would be around 330 kg. Regarding the weight of the new cable configuration, more calculus need to be done to make a good approach.

To size the cross section of the cable, it is necessary to analyze the worst scenario: the one with more power. The voltage is fixed at 3000 V, and the maximum power possible is 2.5 MW. This implies that the maxim possible current is $I = P/V = 2.5 \cdot 10^6/3000 = 833.33$ A. The cable must withdraw this possible maximum current. The regulations establish the cross section for a given current depending on the features of the electrical installation: buried underground, aerial, with or without ventilation... Depending on this features, the cross section goes from 250 mm$^2$ to 500 mm$^2$. It is complicated to know the degree of detail of the electrical installation that the *E-FAN X* will have. So another approach is necessary. It is true that the cross section together with the length of the cable also sizes the voltage losses. Taking into account the dimensions of the *BAe 146-100*, and using again the *OPeRa* tool, the distance between the rear fuselage (where the turboshaft is placed) and the nacelle can be estimated, being its value $L_{T-E} = 17.552$ m. With a preselected cross section of 300 mm$^2$, the losses in voltage would be

$$\Delta V = \frac{2L_{T-E}P_{T-E}}{\sigma V_{T-E}S} = 1.667 \quad \text{V} \quad . \tag{3.28}$$

Where $\sigma$ represents the electrical conductivity of the material, copper in this case, and its value is $58.540 \ \text{m}/\Omega\text{mm}^2$. This value of losses in voltage seems acceptable for this project. Now that the cross section is fixed, the added weight due to the wiring is

$$m_{wiring} = L_{T-E}S\rho_{copper} = 47.180 \quad \text{kg} \quad . \tag{3.29}$$

Taking into account all the assumptions, the new OEW is

$$\begin{aligned} m_{OE,N} = m_{OE,O} - m_{ALF} + m_{AE} + m_{converter} + m_{engine} + m_{wiring} = \\ 23820 \text{ kg} - 606 \text{ kg} + 730 \text{ kg} + 400 \text{ kg} + 330 \text{ kg} + 47.180 \text{ kg} = \\ 24721.180 \text{ kg} \approx 24722 \text{ kg} \quad . \end{aligned} \tag{3.30}$$

The fact of removing one *Lycoming ALF 502R-5* and replace it for a turboshaft, suppose the necessity of adding more devices to transform the movement of the shaft into electricity, carry this electricity to the engine, and convert back the electricity into movement. Table 3.8 summarizes the difference OEW that the two aircraft have. It can be seen that the *E-FAN X* has a OEW 902 kg heavier than the *BAe 146-100*, which means an increase of 3.787%.

**Table 3.8** OEW of the two different aircraft

| *BAe 146-100* (kg) | *E-FAN X* (kg) | Increase (kg) | Percentage increase % |
|---|---|---|---|
| 23820 | 24722 | 902 | 3.787 |

## 3.5 Fuel Consumption and New Seat Layout

With the new OEW, the new maximum number of passenger can be sized, with the requirement that the new configuration must have, with the new MPL, the same range than the old configuration. This means that the range for maximum payload in the new configuration must be the same than the range for maximum payload for the old configuration. For this reason, it is required to do an estimation of the fuel consumption of both configurations.

The fuel consumption estimation developed in this master thesis uses the Breguet equation together with some statistical data. In order to know the fuel consumption for one trip, it is required to analyze the typical profile of a civil mission (Figure 3.5).

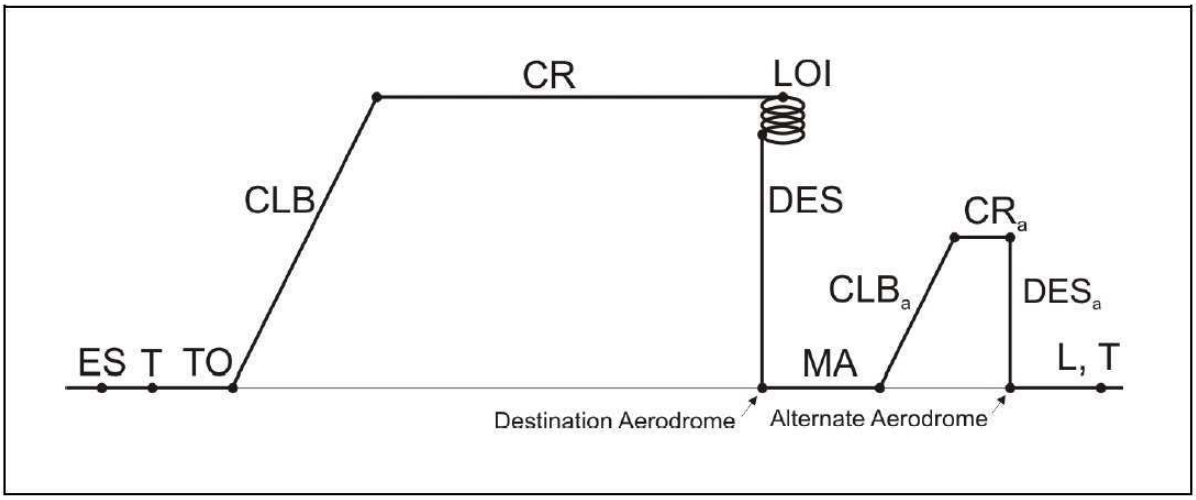


**Figure 3.5** Typical profile of a civil mission (Scholz 2019b)

For the two cruise flight phases, it is necessary to use the Breguet equation, but for the rest of phases, the statistical approaches described in Roskam (1989) have been used. This approaches are fractions between the weight of two following phases. For example, the value corresponding to take off in Table 3.9 refers to the ratio between the weight at the beginning of the climb phase (the following flight phase after the take off) and the weight at the beginning of the take off. For this example, $m_{CLB}/m_{TO} = 0.995$.

**Table 3.9** Generic mission segment mass fractions (Roskam 1989)

| Taxi (T) | Take off (TO) | Climb (CLB) | Descent (DES) | Landing (L) |
|---|---|---|---|---|
| 0.99 | 0.995 | 0.98 | 0.99 | 0.992 |

With this approach, the fuel consumption from the take off to the switch off of the engine can be obtained with the parameter called *Mass Fuel Fraction* ($M_{ff}$). This parameter corresponds to

$$M_{ff} = \frac{m_{SO}}{m_T}\frac{m_T}{m_L}\frac{m_L}{m_{DES}}\frac{m_{DES}}{m_{CR,alt}}\frac{m_{CR,alt}}{m_{CLB}}\frac{m_{CLB}}{m_{MA}}\frac{m_{MA}}{m_{DES}}\frac{m_{DES}}{m_{LOI}}\frac{m_{LOI}}{m_{CR}}\frac{m_{CR}}{m_{CLB}}\frac{m_{CLB}}{m_{TO}} \tag{3.31}$$

Once this parameter is known, the entire mass of fuel consumed in the flight is then calculated as follows

$$m_F = m_{TO} - m_{SO} = m_{TO}\frac{m_{TO} - m_{SO}}{m_{TO}} = m_{TO}\left(1 - M_{ff}\right), \quad \frac{m_F}{m_{TO}} = 1 - M_{ff} \quad . \tag{3.32}$$

The only unknown values are the fractions corresponding to the two cruise flights, and the fraction $m_{DES}/m_{LOI}$. The mass fuel fraction between the descending and the loiter was approximated to 0.99. For the mass fractions corresponding to the cruise, it is only necessary to know the range of the flight, and the Breguet parameter. The mass fraction between the beginning of the cruise and the end of the cruise is then

$$R = Bln\frac{m_{inital}}{m_{final}}, \qquad \frac{m_{final}}{m_{initial}} = e^{-\dfrac{R}{B}} \quad . \tag{3.33}$$

### 3.5.1 Range for MPL for the *BAe 146-100*

The Breguet parameter for the *BAe 146-100* is

$$B_0 = \frac{a_{CR}M_{CR}E_{CR}}{gTSFC_{CR,O}} = 15741 \quad \text{km} \quad . \tag{3.34}$$

The range of the main cruise depends on the route to analyze, and the range of the alternative cruise is object to regulation. There were an attempt to impose in this master thesis what the regulation says about the reserve fuel necessary for this type of aircraft, but the idea was discarded, because, with the simplify models used, the results where completely unreal (range distance to the alternative airport much higher than the range of the main route, and range of 200 km for MPL, among other results). For these reasons, as a trade off, it was decided to take as fuel necessary for the flight, the required for the main route plus 5% of the total amount of fuel weight required for the main flight plus the fuel required for the flight to an alternative airport placed 75 NM away (139 km) with an altitude of 1500 m.

The range for MPL it is unknown in the payload-range diagram for the *BAe 146-100*. In order to know the range for this point, the payload weight was fixed to the MPL value, that is 8612 kg for this aircraft (FLIGHT 2001). Then, several routes with higher range each time were analyzed. In this way, the first route that required MTOW to do a successful flight was the route corresponding to the range with MPL. The first route that generated the MTOW was the route Hamburg-Paris, with a range of 760 km. For the route to the alternative airport, it is not possible to estimate the Breguet parameter correctly. The reasons are that, at the alternative cruise altitude, it is not known the TSFC and the cruise velocity. What is clear is that this Breguet parameter is going to be lower than the Breguet parameter for the cruise. To keep this evaluation as a first approach, the Breguet parameter for this flight phase is going to be the same as the Breguet parameter from the main cruise phase. Thus, the $M_{ff}$, $m_F$ and $m_{TO}$ are

$$\begin{aligned} M_{ff} &= 0.99 \cdot 0.992 \cdot 0.99 \cdot e^{-\dfrac{139}{15741}} \cdot 0.98 \cdot 0.995 \cdot 0.99 \cdot 0.99 \cdot e^{-\dfrac{745}{15741}} \cdot 0.98 \cdot 0.995 \\ &= 0.85575 \quad , \end{aligned} \tag{3.35}$$

$$\begin{aligned} m_{TO} &= m_{OE} + m_{MPL} + m_F = m_{OE} + m_{MPL} + (1 - M_{ff}) m_{TO} \\ m_{TO} &= \frac{m_{OE} + m_{MPL}}{M_{ff}} = \frac{23820\ \text{kg} + 8612\ \text{kg}}{0.85575} = 37898.919\ \text{kg} \quad , \end{aligned} \tag{3.36}$$

$$m_{F,1} = (1 - M_{ff}) m_{TO} = (1 - 0.85575) 37898.919\ \text{kg} = 5466.919 \quad \text{kg} \quad . \tag{3.37}$$

But this value of $m_{TO}$ does not take into account the extra 5% of weight required for the main flight. For this reason, is required to calculate the $M_{ff}$ of the main flight, to obtain the $m_{F,CR}$ and add in this way the extra 5% of fuel necessary.

$$M_{ff,CR} = 0.99 \cdot 0.992 \cdot 0.99 \cdot 0.99 \cdot e^{-\dfrac{760}{15741}} \cdot 0.98 \cdot 0.995 = 0.89433 \tag{3.38}$$

$$m_{F,CR} = (1 - M_{ff,CR}) m_{TO} = (1 - 0.89433) 37898.919\ \text{kg} = 4004.778 \quad \text{kg} \tag{3.39}$$

$$m_{F,TOTAL} = (m_{F,1} - m_{F,CR}) + 1.05 m_{F,CR} = 5667.157 \quad \text{kg} \tag{3.40}$$

In this way, the real $m_{TO}$ is slightly lower than the MTOW, but almost the same. No route with higher range allows this aircraft to take off with MPL and MTOW. For this reason, this route is the route that does the take off with MTOW and MPL.

$$m_{TO} = m_{OE} + m_{MPL} + m_{F,TOTAL} = 23820\ \text{kg} + 8612\ \text{kg} + 5667.157\ \text{kg} = 38099.157 \quad \text{kg} \tag{3.41}$$

The value of the MPL of the *BAE 146-100* together with its maximum number of seats give the pax/weight ratio that must be used during the evaluation of the *E-FAN X*. The maximum number of seats is 82 (FLIGHT 2001), so the ratio is

$$\rho_{pax} = \frac{m_{MPL}}{n_{pax,X}} = \frac{8612\ \text{kg}}{82} = 105.024 \quad \text{kg/pax} \quad . \tag{3.42}$$

### 3.5.2 Fuel Consumption for the *E-FAN X*

The reduction in the fuel consumption for the *E-FAN X* is achieved in two different ways. The first and simple way is by the change of the Breguet parameter. Due to the reduction of the TSFC, and because the rest of the parameters remain equal, the Breguet parameter will we higher. This means a reduction of the fuel consumed during the cruise phase, and also during the cruise to the alternative airport. The new Breguet parameter for the cruise is then

$$B_N = \frac{a_{CR} M_{CR} E_{CR}}{g TSFC_{CR,N}} = 15821 \quad \text{km} \tag{3.43}$$

But there is another effect of fuel consumption reduction that was taken into account, an effect that plays in favour to this new configuration. The idea is that, for a given equal weight for the two aircrafts, the new aircraft will have a fuel consumption reduced by 0.506% in all the flight phases, except for the take off phase, where the reduction is 9.146%. This different fuel consumption are the differences established in Table 3.6. What this idea pretends to represent is that in every flight phase of the new configuration, the new aircraft have less fuel consumption. The exactly amount of reduction is not known, as further research would be necessary. But in order to take into account this effect, a first approach was accomplished using the reduction of the cruise as the reduction for every phase, except for the take off, where the reduction is known. With this reduction of fuel consumption, the values given in Table 3.9 are different for the new aircraft, and are calculated as follows.

The first assumption is that for a given flight phase A, both configurations have the same weight

$$W_{A,O} = W_{A,N} \quad . \tag{3.44}$$

The mass fuel fraction between the phase A and the following phase B is known in the old configuration, as the values are gathered in Table 3.9. But this mass fuel fraction can also be written as a function of the weight at the beginning of the phase A and the fuel consumed between A and B.

$$\frac{W_{B,O}}{W_{A,O}} = \alpha = \frac{W_{A,O} - FW_{A-B,O}}{W_{A,O}} = 1 - \frac{FW_{A-B,O}}{W_{A,O}}, \quad FW_{A-B,O} = (1-\alpha) W_{A,O} \tag{3.45}$$

Now this fuel weight required in the old configuration can be related with the fuel weight required in the new configuration, using the known reduction in fuel consumption

$$FW_{A-B,N} = (1-\beta) FW_{A-B,O} \quad . \tag{3.46}$$

The parameter $\beta$ represents the reduction in fuel consumption of the new configuration (Table 3.6). The new mass fuel fraction between the phases A and B can now be calculated with the following expression

$$\frac{W_{B,N}}{W_{A,N}} = \frac{W_{A,N} - FW_{A-B,N}}{W_{A,N}} = 1 - \frac{FW_{A-B,N}}{W_{A,N}} = 1 - \frac{FW_{A-B,N}}{W_{A,O}} = \\ = 1 - \frac{(1-\beta)FW_{A-B,O}}{W_{A,O}} = 1 - (1-\beta)(1-\alpha) = \alpha + \beta - \alpha\beta \quad . \tag{3.47}$$

Applying this to all the flight phases, all the mass fractions can be known. The new values of mass fractions are gathered in Table 3.10.

**Table 3.10** Estimation of the new mass fuel fractions

| | Taxi (T) | Take off (TO) | Climb (CLB) | Descent (DES) | Landing (L) |
|---|---|---|---|---|---|
| $\alpha$ | 0.99 | 0.995 | 0.98 | 0.99 | 0.992 |
| $\beta$ | 0.00506 | 0.09146 | 0.00506 | 0.00506 | 0.00506 |
| NEW | 0.99005 | 0.99546 | 0.98010 | 0.99005 | 0.99204 |

### 3.5.3 New Number of Seats

Once the new OEW is known, the fuel consumption method is defined, the range for the MPL is obtained for the *BAe 146-100*, and the new fuel consumption for the *E-FAN X* is settled, it is possible to obtain the new maximum number of passengers.

The route that the new aircraft has to cover with its new MPL is the same as the old aircraft: Hamburg-Paris. The range is then 760 km. The difference now in the calculation is that the TOW can not be known, because is not known the MPL. Hence, there is an equation that generates a relationship between $m_{TO}$ and $m_{MPL}$, that also means a relationship between $m_F$ and $m_{MPL}$. Using the Equation 3.31 with the new mass fuel fractions (Table 3.10), the $M_{ff}$, $m_{TO}$ and $m_F$ are related to the MPL as follows

$$M_{ff} = 0.99005 \cdot 0.99204 \cdot 0.99005 \cdot e^{-\frac{139}{15821}} \cdot 0.98010 \cdot 0.99546 \cdot \\ \cdot 0.99005 \cdot 0.99005 \cdot e^{-\frac{760}{15821}} \cdot 0.98010 \cdot 0.99546 = 0.85684 \quad , \tag{3.48}$$

$$m_{TO} = m_{OE} + m_{MPL} + m_F = m_{OE} + m_{MPL} + (1 - M_{ff})m_{TO} \\ m_{TO} = \frac{m_{OE} + m_{MPL}}{M_{ff}} = \frac{24722 \text{ kg} + m_{MPL}}{0.85684} \quad , \tag{3.49}$$

$$m_{F,1} = (1 - M_{ff})m_{TO} = (1 - 0.85684)\frac{24722 \text{ kg} + m_{MPL}}{0.85684} \quad . \tag{3.50}$$

It is the same for the cruise fuel weight

$$M_{ff,CR} = 0.99005 \cdot 0.99204 \cdot 0.99005 \cdot 0.99005 \cdot e^{-\frac{760}{15821}} \cdot 0.98010 \cdot 0.99546 = 0.89522 \quad , \tag{3.51}$$

$$m_{F,CR} = (1 - M_{ff,CR}) m_{TO} = (1 - 0.89522) \frac{24722 \text{ kg} + m_{MPL}}{0.85684} \quad . \tag{3.52}$$

The total amount of fuel weight required is a function of the $m_{MPL}$.

$$m_{F,TOTAL} = (m_{F,1} - m_{F,CR}) + 1.05 m_{F,CR} = m_{F,1} + 0.05 m_{F,CR} \tag{3.53}$$

The real relationship between $m_{TO}$ and $m_{MPL}$, with the contingencies added to the fuel weight, is in this way

$$m_{TO} = m_{OE} + m_{MPL} + m_{F,TOTAL} = 24722 \text{ kg} + m_{MPL} + (1 - 0.85684) \frac{24722 \text{ kg} + m_{MPL}}{0.85684} + \\ + 0.05(1 - 0.89522) \frac{24722 \text{ kg} + m_{MPL}}{0.85684} = 1.1730 m_{MPL} + 29003.686 \text{ kg} \quad . \tag{3.54}$$

Using the value of MTOW as value for the $m_{TO}$, the $m_{MPL}$ is given, and then the maximum number of passengers

$$38102 \text{ kg} = 1.173 m_{MPL} + 29003.686 \text{ kg}, \quad m_{MPL} = 7756.448 \quad \text{kg} \quad , \tag{3.55}$$

$$n_{pax,X,N} = \frac{m_{MPL}}{\rho_{pax}} = \frac{7756.448 \text{ kg}}{105.024} = 73.85 = 73 \quad \text{pax} \quad . \tag{3.56}$$

The maximum number of passengers for the *E-FAN X* is then establish in 73, and its MPL to 7667 kg. This supposes a reduction in the number of seats of $(73 - 82)/82\ \% = -10.97\%$, a non negligible value. With the exact value of the MPL, the real $m_{TO}$ for this flight is slightly lower than the MTOW.

$$m_{TO} = 1.173 m_{MPL} + 29003.686 \text{ kg} = 1.173 \cdot 73 \cdot 105.024 \text{ kg} + 28974.593 \text{ kg} = 37997.077 \quad \text{kg} \tag{3.57}$$

The fuel weight required for this flight is then

$$m_{F,TOTAL} = m_{TO} - m_{MPL} - m_{OE} = 37997.077 \text{ kg} - 7667 \text{ kg} - 24722 \text{ kg} = 5608.077 \quad \text{kg} \quad . \tag{3.58}$$

The new aircraft would carry 10.97% less passengers for the same distance with a different in the fuel required of $(5608.077 - 5667.157)/5667.157\ \% = -1.042\%$. These results can be seen in Table 3.11.

**Table 3.11** Weights of the two aircraft for the same design route

| | OEW (kg) | $m_{F,TOTAL}$ (kg) | MPL (kg) | $n_{pax}$ |
|---|---|---|---|---|
| *Bae 146-100* | 23820 | 5667 | 8612 | 82 |
| *E-FAN X* | 24722 | 5608 | 7667 | 73 |
| Increase | 902 | -59 | -945 | -9 |
| Percentage difference (%) | 3.787 | -1.042 | -10.97 | -10.97 |

The reduction in the fuel for the route is not enough to cover the increase of the OEW due to the new devices required for the hybrid propulsion. This increase of weight is then covered by the loss of seats. Otherwise it is not possible to make the flight with the same requirements: same MTOW and same range for MPL.

This loss of seats would be even higher if the new aircraft would have to carry on board the battery. The OEW would be increased in 2 tons. But the presence of the battery would also affect to the fuel consumption, making it lower in the take off flight phase, but higher in the cruise phase where the recharge take place. Depending on the energy to recharge, but also the time that the recharge takes, this fuel consumption can be lower, equal or higher than the fuel consumption for the old configuration. It can be seen that, in this scenario, the loss of seats would be even more numerous.

### 3.5.4 Seat Layout Comparison

With the different number of seats, a different seat layout will be necessary for each aircraft. The different seat layout generates differences in the economic area. An aircraft with more or less first class seats has a different incomes and expenses than an aircraft with more or less economic class seats. It is necessary then to know the old seat layout, and to design the new seat layout. For this reason, to obtain the seat layout of both aircraft, it has been used the *PreSTo* tool, another tool of the *Aircraft Design and Systems Group* (AERO 2011). Introducing some parameters of the aircraft, this tool gives back the seat layout of that aircraft.

For the *BAe 146-100* it is known that the number of passengers is 82, and that the layout is 5 seats abreast. Only with the economic class it is not possible to fill an entire number of rows. For this reason, some seats of first class are added. In this way it can be optimized the space and rows. The *PReSTo* tool generates then a layout with 70 seats for the economic class in 14 rows, and 12 seats for the first class in 4 rows. The seat layout for the *BAe 146-100* is shown in Figure 3.6.

Regarding the *E-FAN X*, the number of seats is 73. The layout should be again with 5 seats abreast. This means that the optimum configuration is 14 rows of economic class and 1 row of first class. The number of seats is then 70 for the economic class, and 3 for the first class. Figure

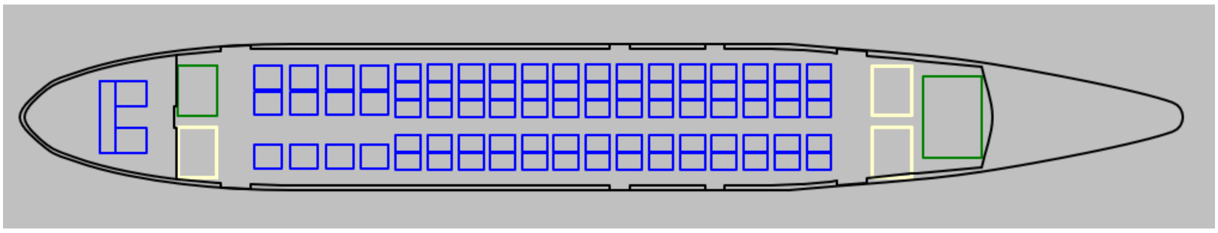

**Figure 3.6** Seat layout for the *BAe 146-100* by AERO (2011)

3.7 shows the seat layout for the *E-FAN X*.

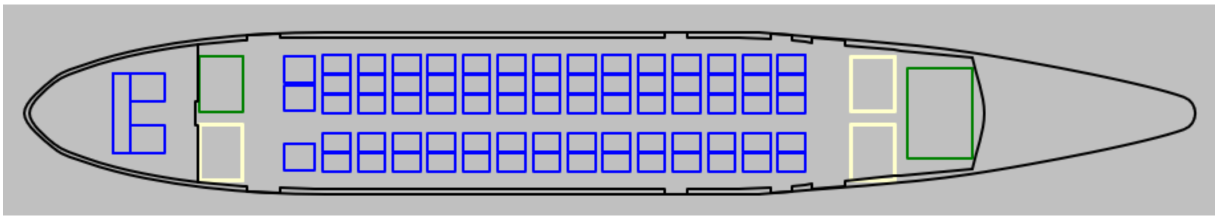

**Figure 3.7** Seat layout for the *E-FAN X* by AERO (2011)

Due to the reduction of seats, it seems that the new configuration will have more space in the cabin. But the location of the *AE 2100A* will also require space. And its location is in the rear fuselage. This means that the increase in space due to the less number of seats will be balanced with the decrease of space due to the turboshaft.

Figure 3.8 represents the cross section of the fuselage. It shows the layout for one first class row and one economic class row. This cross section is as valid for the *BAe 146-100* as for the *E-FAN X*. Table 3.12 contains the number of seats per class of each aircraft

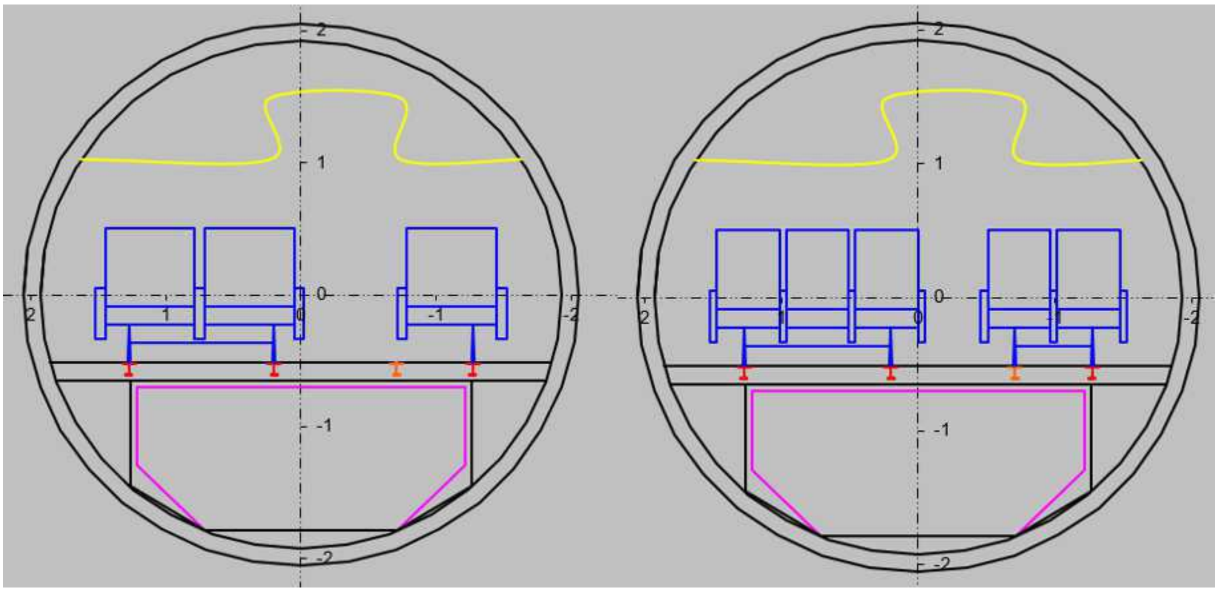

**Figure 3.8** Cross section for the *BAe 146-100* and *E-FAN X* by AERO (2011)

**Table 3.12** Number of seats per class and aircraft

| Aircraft | First class | Economic class | Total |
|---|---|---|---|
| *BAe 146-100* | 12 | 70 | 82 |
| *E-FAN X* | 3 | 70 | 73 |

As it is explained in Chapter 5, for the environmental analysis is not only important the different number of seats, but also the relative space that they occupy. It is necessary then to obtain the area occupied for each class, and the relative surface the seats of each class occupy in both aircraft. The surface on one seat is

$$S_{seat} = PseatWseat \quad . \tag{3.59}$$

Where the variable $P_{seat}$ is referred to the pitch of the seat, and the variable $W_{seat}$ is referred to the width of the seat.

The standard values for each class are, according to Scholz 2019b, listed in Table 3.13. Then the surface occupied by each class, and its percentage value can be calculated. These values are gathered in Table 3.14, and they have been calculated with the information of Table 3.12.

**Table 3.13** Dimensions for each seat class by Scholz (2019b)

| Class | Pitch (m) | Width (m) | Surface (m$^2$) |
|---|---|---|---|
| First class | 0.99 | 0.61 | 0.604 |
| Economic class | 0.86 | 0.51 | 0.438 |

**Table 3.14** Surface occupied per each class in each aircraft

| | First class | | Economic class | |
|---|---|---|---|---|
| Aircraft | Surface (m$^2$) | Percentage (%) | Surface (m$^2$) | Percentage (%) |
| *BAe 146-100* | 7.25 | 19.12 | 30.66 | 80.88 |
| *E-FAN X* | 1.81 | 5.58 | 30.66 | 94.42 |

# 4 Economical Analysis

The first analysis that takes place is the economic analysis. The transformation of the aircraft from the *BAe 146-110* to the *E-FAN X* generates differences that have a repercussion in the economic area. The new configuration, new fuel consumption and new number of seats are going to change the economic results. In this master thesis, the DOC method that has been used is the AEA 1989a method, which is gathered in Scholz (2019b). This method is used by the *Association of European Airlines*.

To do the comparison, several routes has been analyzed in a simulation of one year of flights. The results shown in this chapter are going to be the results for the routes established in Table 4.1. This table shows for each route, the range, the flight time, the block time and the flights per year. Following the AEA 1989a method, the block time is estimated as the flight time plus 0.25 hours. The flight time maintains a relationship with the number of flights per year. It is not possible to set a number of flights per year without taking into account the flight time. Once the flight time is fixed, the maximum number of flights per year are fixed, thanks to the utilization formula. The way of doing the comparison among this routes is then with the DOC per seat mile. With this ratio, the three routes, and every route, can be compared.

**Table 4.1** Routes analyzed in the economical analysis

| Route | Range (km) | Flight Time (h) | Block Time (h) | Flights per year |
|---|---|---|---|---|
| Hamburg - Prague | 500 | 1.08 | 1.32 | 2050 |
| Hamburg - Paris | 760 | 1.38 | 1.63 | 1758 |
| Hamburg - Marseilles | 1180 | 1.88 | 2.13 | 1426 |

The route from Hamburg to Paris is the range for MPL. Hence, the route from Hamburg to Prague has also MPL, but the take off weight is not MTOW, it is lower. The route from Hamburg to Marseilles has a higher range which means the take off weight is MTOW but not with MPL.

In order to do a DOC analysis, there are necessary some unknown data. For this reason, this method has some estimations about several required values. This estimations are done in USD of 1989. It is required then for each calculus to do the actualization from 1989 to 2019. The actualization is done adding the inflation factor $k_{inf}$ wherever is necessary. The value for this factor is

$$1 \text{ USD from } 1989 = 2.08 \text{ USD from } 2019, \quad k_{inf} = 2.08 \tag{4.1}$$

This DOC method divides the expenses in seven different areas: depreciation, interest, insurance, fuel cost, maintenance, staff and fees. The three first areas are independent of the number of flights and flight time, they have a fixed value per year. But the other four areas depends on the utilization of the aircraft. The higher the number of flights and flight time, the higher the expense.

In the following subsections the cost for each area is calculated for both aircraft.

## 4.1 Depreciation

The depreciation is the distribution of the reduction in value of the aircraft over the useful service life. It depends on the total purchase price of the aircraft, the useful service life over which the aircraft is to be depreciated, and the residual value that which the aircraft can be sold at the end of its use. The depreciation is then

$$C_{DEP} = \frac{P_{TOTAL} - P_{RESIDUAL}}{n_{DEP}} = \frac{P_{TOTAL}\left(1 - \frac{P_{RESIDUAL}}{P_{TOTAL}}\right)}{n_{DEP}} \quad . \tag{4.2}$$

The total purchase price of an aircraft comprises the delivery price of the overall aircfraft and the price for the spares.

$$P_{TOTAL} = P_{DEL} + P_S \tag{4.3}$$

The delivery price is not known, but several estimations can be done depending on the MTOW, OEW and $n_{pax,X}$. With this different prices, an average is done to estimate the delivery price (Table 4.2).

**Table 4.2** Delivery price of the *BAe 146-100*

| | Estimation | Price (USD) | Price with inflation (USD) |
|---|---|---|---|
| MTOW | 500 (USD/kg) | 19051000 | 39626080 |
| OEW | 860 (USD/kg) | 20485200 | 42609216 |
| $n_{pax,X}$ | 265000 (USD/pax) | 21730000 | 45198400 |
| | Average | | 42477898 |

As the transformation of the aircraft is done replacing one engine, the delivery price of the *E-FAN X* can be obtained subtracting the price of one *ALF 502R-5* and adding the price of one *AE 2100A*. The price of the *ALF 502R-5* is not known, reason why it has been used the estimation for the price given by this method. This estimation is based on the take off thrust of the engine.

$$P_E = 293 T_{TO}^{0.81} k_{inf} = 2648097 \quad \text{USD} \tag{4.4}$$

The price of the *AE 2100A* is known and given in Table 3.3. Hence, the delivery price for the *E-FAN X* is

$$P_{DEL,N} = P_{DEL,O} - P_{E,O} + P_{E,N} = 42929801 \quad \text{USD} \tag{4.5}$$

Regarding the spares price, this price is calculated from a proportion of the price of the airframe and a proportion of the price of the engines. The values of $k_{S,AF}$ and $k_{S,E}$ are, for this sort of aircraft, 0.1 and 0.3 respectively.

$$P_S = k_{S,AF}P_{AF} + k_{S,E}n_EP_E = 0.1P_{AF} + 0.3n_EP_E \tag{4.6}$$

Because of the difference in the engine price, the prices for spares is different for each aircraft. But it is first necessary to know the price of the airframe. Due to the airframe of both aircraft is identical, the airframe price is the same in both configurations. The only difference the two aircraft have is the engine. Hence, the airframe price of *BAe 146-100* can be obtained, settling in this way the airframe price of the *E-FAN X*. This airframe price has been calculated with Equation 4.7, using the price of the engines calculated in Equation 4.4. Once obtained this value, the price of the spares for the different configurations can be obtained.

$$P_{AF} = P_{DEL} - n_EP_E = 31885510 \quad \text{USD} \tag{4.7}$$

$$P_{S.O} = 6366267 \quad \text{USD} \tag{4.8}$$

$$P_{S.N} = k_{S,AF}P_{AF} + k_{S,E}(3P_{E,O} + P_{E,N}) = 6501838 \quad \text{USD} \tag{4.9}$$

The last value necessary to know is the ratio $P_{RESIDUAL}/P_{TOTAL}$ and the $n_{DEP}$. The method says that, for this kind of aircraft, the ratio is 0.1 and the years of depreciation are 14. With all the necessary values known, the depreciation results are shown in Table 4.3. These values of depreciation are independent of the time flight and number of flights, so they are the same for the three routes analyzed.

**Table 4.3** Depreciation

| | Spares (USD) | Delivery (USD) | TOTAL (USD) | $C_{DEP}$ (USD/year) |
|---|---|---|---|---|
| *BAe 146-100* | 6366267 | 42477898 | 48844166 | 3139982 |
| *E-FAN X* | 6501838 | 42929801 | 49431639 | 3177748 |

## 4.2 Interest

The interest take into account the real price that has to be paid to the investor. It is assumed that the total price invested in the new aircraft is financed by outside sources.

$$C_{INT} = p_{av}P_{TOTAL} \tag{4.10}$$

A detailed version of the value of the interest assumes that the outside capital will be repaid in equal installments and annual payments $a$ at the end of the year over $n_{pay}$ years. After the $n_{pay}$ years, a relative residual value $P_N/P_{TOTAL}$ of the outside capital may then remain in the company. In order to calculate the average interest, the approximation to $a$ is given as

$$a = \frac{P_{TOTAL}\left(q^{n_{PAY}} - \frac{P_N}{P_{TOTAL}}\right)(q-1)}{q^{n_{pay}} - 1} \quad . \tag{4.11}$$

To calculate an average interest rate, these interest payments are spread over $n_{DEP}$ years during which the aircraft is depreciated. Per year this comes to interest of

$$C_{INT} = \frac{a n_{PAY} - P_{TOTAL}\left(1 - \frac{P_n}{P_{TOTAL}}\right)}{n_{DEP}} = p_{av} P_{TOTAL} \quad . \tag{4.12}$$

The average interest $p_{av}$ is known as far as all of the parameters involved in the calculation are given in the method. The value of all this parameters are gathered in Table 4.4.

$$p_{av} = \frac{\frac{\left(q^{n_{PAY}} - \frac{P_N}{P_{TOTAL}}\right)(q-1)}{q^{n_{pay}} - 1} - \left(1 - \frac{P_n}{P_{TOTAL}}\right)}{n_{DEP}} \tag{4.13}$$

**Table 4.4** Interest parameters

| $p$ | $q = p + 1$ | $n_{PAY}$ | $P_N/P_{TOTAL}$ | $n_{DEP}$ | $p_{av}$ |
|---|---|---|---|---|---|
| 0.08 | 1.08 | 14 | 0.1 | 14 | 0.052881 |

The value of the average interest is the same for both aircraft. With the total price calculated in Table 4.3, the value of the interest for each aircraft, and for every route analyzed, is shown in Table 4.5.

**Table 4.5** Interest

| | $C_{INT}$ (USD/year) |
|---|---|
| *BAe 146-100* | 2582950 |
| *E-FAN X* | 2614016 |

## 4.3 Insurance

The costs caused by insuring the aircraft against hull damage or even against hull loss are calculated as a percentage of the aircraft price. The results can be seen in Table 4.6

$$C_{INS} = k_{INS} P_{TOTAL} \tag{4.14}$$

**Table 4.6** Insurance

| | $k_{INS}$ | $P_{TOTAL}$ (USD) | $C_{INS}$ (USD/year) |
|---|---|---|---|
| *BAe 146-100* | 0.005 | 48844166 | 212389 |
| *E-FAN X* | | 49431639 | 214649 |

## 4.4 Fuel Cost

For the fuel cost, the fuel consumption estimation done in the Section 3.5 has been used for each route. But only the cost of the fuel consumed during the main flight has been taken into account in the fuel cost. The fuel required for the flight to the alternative airport is only consumed during emergencies. For this reason, the only fuel cost that can be deducted is the fuel cost of the amount of fuel consumed during the main flight.

Once the expected fuel consumed is obtained, it is only necessary to known the number of barrels per year that are required, and multiply this number of barrels for the price of each barrel. The price of the barrel is known today, so it is not required to use the inflation factor. One barrel of kerosene has a volume of 159 L, and a current price of 80 USD. Due to the fuel consumption estimation gives the mass of the fuel consumed, in order to obtain the volume of fuel required for the flight, it is just necessary to divide the amount of fuel by its density ($\rho_{kerosene} = 0.804$ kg/L ).

Table 4.7 contains the information about to fuel cost for each route.

**Table 4.7** Fuel cost

| Hamburg - Prague | | | | | |
|---|---|---|---|---|---|
| | Fuel (kg) | Flights p.y. | Fuel p.y. (kg) | Barrels p.y. | $C_F$ (USD/year) |
| *BAe 146-100* | 3384 | 2050 | 6937200 | 54267 | 4341200 |
| *E-FAN X* | 3343 | | 6853150 | 53618 | 4289440 |
| **Hamburg - Paris** | | | | | |
| | Fuel (kg) | Flights p.y. | Fuel p.y. (kg) | Barrels p.y. | $C_F$ (USD/year) |
| *BAe 146-100* | 4004 | 1758 | 7039032 | 55074 | 4405920 |
| *E-FAN X* | 3959 | | 6959922 | 54451 | 4356080 |
| **Hamburg - Marseilles** | | | | | |
| | Fuel (kg) | Flights p.y. | Fuel p.y. (kg) | Barrels p.y. | $C_F$ (USD/year) |
| *BAe 146-100* | 5030 | 1426 | 7172780 | 56105 | 4488400 |
| *E-FAN X* | 4976 | | 7095776 | 55509 | 4440720 |

## 4.5 Maintenance Cost

The equations for calculating maintenance costs normally take the biggest space when using DOC methods. The estimations about the cost of the maintenance are complex and depend on numerous factors. There is no experience with the maintenance of the electrical propulsion, and thus there is a lack of models or methods in this area. For this reasons, any attempt to estimate the changes in the different maintenance of the different aircraft was discarded. Due to the many factors involved in the maintenance cost, and in terms of keeping a first evaluation of the project, the maintenance cost for both aircraft has been established as the same.

It was calculated the maintenance cost for the *BAe 146-100*, and this results were used for the *E-FAN X* too. These maintenance cost are directly proportional to the flights per year and the flight time. But the flights per year have more weight in this calculation than the time flight, as it can be seen in Table 4.8.

It has to be mentioned that, despite of setting the maintenance cost as the same for both aircraft, this cost is expected to be higher for the new configuration. The reason is simple: having four equal engines makes the maintenance cheaper than having three equal engines and one different engine. Two different kind of maintenance are required for the *E-FAN X*. Only one kind of maintenance for the *BAe 146-100*. This means that the assumption made about the maintenance cost plays in favour of the *E-FAN X*, and would make its DOC lower than the real result.

**Table 4.8** Maintenance cost

| Hamburg - Prague | | | |
|---|---|---|---|
| | Time flight (h) | Flights per year | $C_M$ (USD/year) |
| *BAe 146-100*<br>*E-FAN X* | 1.08 | 2050 | 5559074 |
| **Hamburg - Paris** | | | |
| | Time flight (h) | Flights per year | $C_M$ (USD/year) |
| *BAe 146-100*<br>*E-FAN X* | 1.38 | 1758 | 5387420 |
| **Hamburg - Marseilles** | | | |
| | Time flight (h) | Flights per year | $C_M$ (USD/year) |
| *BAe 146-100*<br>*E-FAN X* | 1.88 | 1426 | 5193829 |

## 4.6 Staff Cost

The staff cost depends on the number of crew required for the flight, the block time, the number of flights per year, and the salary of the cockpit crew and cabin crew. For an aircraft with a number of passengers between 50 and 100, only 2 people for cabin crew are required. This means that the results for both aircraft are the same. The average salary for cockpit crew is $L_{CO} = 246.5$ USD/h, and the average salary for the cabin crew is $L_{CC} = 81$ USD/h. These values need to be updated with the inflation factor. The cost of the staff crew is then

$$C_{SC} = (n_{CO}L_{CO} + n_{CC}L_{CC})\, t_b n_{fpy} k_{inf} \tag{4.15}$$

The staff cost is shown in Table 4.9

**Table 4.9** Staff Cost

| | Time block (h) | Flights per year | $C_{SC}$ (USD/year) |
|---|---|---|---|
| Hamburg - Prague | | | |
| *BAe 146-100*<br>*E-FAN X* | 1.33 | 2050 | 3714583 |
| Hamburg - Paris | | | |
| *BAe 146-100*<br>*E-FAN X* | 1.63 | 1758 | 3911915 |
| Hamburg - Marseilles | | | |
| *BAe 146-100*<br>*E-FAN X* | 2.13 | 1426 | 4138126 |

## 4.7 Fees and Charges

Three different kind of fees can be deducted in the DOC calculation: the landing fees, the navigation fees, and the ground fees. The landing fees depend on the maximum take off mass, the navigation charges depend on the flight distance and the maximum take off mass, and the ground handling charges depend on the maximum payload weight. The equations that give the value for each fee and charge are Equations 4.16, 4.17 and 4.18. The different value for the different fees and charges are gathered in Table 4.10, 4.11, 4.12.

$$C_{FEE,L} = MTOW\, k_{LD} n_{fpy} k_{inf}, \quad k_{LD} = 0.078 \quad \text{USD/kg} \tag{4.16}$$

$$C_{FEE,NAV} = R\sqrt{MTOW}k_{NAV}n_{fpy}k_{inf}, \quad k_{NAV} = 0.00766 \quad \text{USD/km}\sqrt{\text{kg}} \tag{4.17}$$

$$C_{FEE,GND} = MPLk_{GND}n_{fpy}k_{inf}, \quad k_{GND} = 0.1 \quad \text{USD/kg} \tag{4.18}$$

**Table 4.10** Landing fees

| Hamburg - Prague | | | |
|---|---|---|---|
| | MTOW (kg) | Flights per year | $C_{FEE,LD}$ (USD/year) |
| *BAe 146-100*<br>*E-FAN X* | 38102 | 2050 | 1267242 |
| **Hamburg - Paris** | | | |
| | MTOW (kg) | Flights per year | $C_{FEE,LD}$ (USD/year) |
| *BAe 146-100*<br>*E-FAN X* | 38102 | 1758 | 1086737 |
| **Hamburg - Marseilles** | | | |
| | MTOW (kg) | Flights per year | $C_{FEE,LD}$ (USD/year) |
| *BAe 146-100*<br>*E-FAN X* | 38102 | 1426 | 881506 |

**Table 4.11** Navigation fees

| Hamburg - Prague | | | | |
|---|---|---|---|---|
| | MTOW (kg) | Range (km) | Flights per year | $C_{FEE,NAV}$ (USD/year) |
| *BAe 146-100* <br> *E-FAN X* | 38102 | 500 | 2050 | 3190820 |
| **Hamburg - Paris** | | | | |
| | MTOW (kg) | Range (km) | Flights per year | $C_{FEE,NAV}$ (USD/year) |
| *BAe 146-100* <br> *E-FAN X* | 38102 | 760 | 1758 | 4159211 |
| **Hamburg - Marseilles** | | | | |
| | MTOW (kg) | Range | Flights per year | $C_{FEE,NAV}$ (USD/year) |
| *BAe 146-100* <br> *E-FAN X* | 38102 | 1180 | 1426 | 5238175 |

**Table 4.12** Ground fees

| Hamburg - Prague | | | |
|---|---|---|---|
| | MPL (kg) | Flights per year | $C_{FEE,GND}$ (USD/year) |
| *BAe 146-100* | 8612 | 2050 | 4039203 |
| *E-FAN X* | 7667 | | 3596130 |
| **Hamburg - Paris** | | | |
| | MPL (kg) | Flights per year | $C_{FEE,GND}$ (USD/year) |
| *BAe 146-100* | 8612 | 1758 | 3463863 |
| *E-FAN X* | 7667 | | 3083901 |
| **Hamburg - Marseilles** | | | |
| | MPL (kg) | Flights per year | $C_{FEE,GND}$ (USD/year) |
| *BAe 146-100* | 8612 | 1426 | 2809709 |
| *E-FAN X* | 7667 | | 2501503 |

It can be seen that the reduction in the MPL has an unexpected benefit for the *E-FAN X*: the reduction in the ground fees. This reduction is much higher that the reduction achieved with the reduction in the fuel consumption.

The total cost for each route is the sum of each fee and charge, and the result is shown in Table 4.13

$$C_{FEE} = C_{FEE,L} + C_{FEE,NAV} + C_{FEE,GND} \tag{4.19}$$

**Table 4.13** Fees and charges cost

| Hamburg - Prague | | | | |
|---|---|---|---|---|
| | $C_{FEE,LD}$ | $C_{FEE,NAV}$ | $C_{FEE,GND}$ | $C_{FEE}$ (USD/year) |
| *BAe 146-100* | 1267242 | 3190820 | 4039203 | 8497265 |
| *E-FAN X* | | | 3596130 | 8054192 |
| **Hamburg - Paris** | | | | |
| | $C_{FEE,LD}$ | $C_{FEE,NAV}$ | $C_{FEE,GND}$ | $C_{FEE}$ (USD/year) |
| *BAe 146-100* | 1086737 | 4159211 | 3463863 | 8709811 |
| *E-FAN X* | | | 3083901 | 8329849 |
| **Hamburg - Marseilles** | | | | |
| | $C_{FEE,LD}$ | $C_{FEE,NAV}$ | $C_{FEE,GND}$ | $C_{FEE}$ (USD/year) |
| *BAe 146-100* | 881506 | 5238175 | 2809709 | 8929389 |
| *E-FAN X* | | | 2501503 | 8621184 |

## 4.8 DOC Results

The DOC results per year consist in the sum of the expenses of all the areas

$$C_{DOC} = C_{DEP} + C_{INT} + C_{INS} + C_F + C_M + C_{SC} + C_{FEE} \tag{4.20}$$

The results can be addressed in so many ways. For this reason, a combination of tables and figures are used to explain all the differences. But the results for each route follow the same structure. The total DOC value for the new aircraft is slightly lower than the DOC value of the old aircraft. The new engine makes the new aircraft more expensive, so the depreciation, interest and insurance are higher. The reduction in the fuel consumption generates a save in money, but its impact is so small. The real fact that saves money is the decreasing in the maximum number of passengers, that generates a lower value of the fess and charges. In order to compare both DOC values, it is required to take into account the number of miles that both aircraft do (same in each route) and the number of seats transported (different). With the value of the DOC per seat mile, the comparison can be perfectly done.

In every case, the DOC per seat mile of the new aircraft is higher. This is due to the reduction in the maximum number of passengers. The new engine generates a slightly reduction in the fuel consumption but a significant increase in the OEW, that makes necessary a reduction in the maximum number of passengers to maintain the same requirements as the old aircraft. The new engine makes the new aircraft more expensive, heightening the price of the aircraft, and making higher the depreciation, interest an insurance. The reduction in fuel consumption generates a save in money, but not enough to cover the increase of the three mentioned factor. The new MPL is what generates the real reduction in the DOC. All together produce a lower DOC, that would save money with the same maximum number of passengers. The real effect that saves more money is then the reduction in the MPL. This effect was not sought with the replacement of the engine. It was sought to achieve a reduction of the DOC with the reduction in the fuel consumption, and with the same number of passengers.

Starting with the comparison for each route, the results can be seen in Tables 4.14, 4.15, 4.16. Figures 4.1, 4.2, 4.3 are pie charts that represent the percentage of expenses for each route and aircraft. The increase of the range supposes and increase on the time flight, but a reduction in the number of flight per year. This generates some differences in the value of the fuel cost, maintenance cost, staff cost and fees and charges. For the fuel cost, the grow in the amount of fuel necessary is greater than the decrease in the number of flights per year. The multiplication of this two factors increase with the increase of the range. For that reason the fuel cost is higher in the Hamburg - Marseilles route. For the staff cost the effect is similar. The heightening of the time flight compensates the reduction of the number of flights per year, generating a greater value for the higher routes. Regarding the fees and charges, it is directly proportional to the range and the number of flights per year. And again, the increase of the range is higher than the reduction in the number of flights per year. For the maintenance cost, the most important value is the number of flights per year. With the decrease in this value, the maintenance cost also decreases, as it can be seen in the results. The combination of all of this, generates a value of DOC that is higher for the routes with more range. The differences between both DOC total values decreases with the increase in the range. This percentage difference goes from -1.511% for the route Hamburg - Prague to -0.992% for the route Hamburg - Marseilles. Hence, it seems that the new aircraft would save more money in the short range routes. This is due to the percentage difference between fuel cost and fees and charges for both aircraft are higher when the range is lower. In the fuel case, because the total value of fuel consumed is lower, so in the calculus of the percentage difference, the difference in fuel consumed is divided for a lower number, generating a more negative percentage difference. Regarding the fees and charges, the reduction in range has more impact that the reduction in number of flights. For that reason the short routes are more beneficial in this aspect.

From the pie charts (Figures 4.1, 4.2, 4.3) it can be concluded that the fees and charges are the expenses with the higher impact in the DOC evaluation, followed by maintenance cost and the fuel cost. The reduction in the total DOC value for the *E-FAN X* makes that fees and charges have a less percentage than the percentage for the same area in the *BAe146-100*. This effect is in detriment of the rest of the areas, that have a slightly higher percentage in the new configuration in respect of the old configuration. The differences narrow for the route with more range, due to the total value of the DOC also narrows

Taking a look to the DOC per seat mile results, the value for the *E-FAN X* is always higher, due to the reduction in the number of seats. The DOC per seat mile decreases with the increase of the range for both aircraft. But the percentage difference between this two aircraft grows with the increase of the range. It has to be mentioned that, for the route Hamburg - Marseilles, both aircraft do the flights not with the maximum number of passenger but with less, due to the amount of fuel required.

With the DOC per seat mile results, it also can be concluded that it is more expensive to cover the same route with the *E-FAN X*. The revenues per seat needs to be increased if it is wanted to make this flight profitable. But a higher prices for the tickets would make this flight less competitive in the market. Hence, the economical evaluation of this transformation says that the new aircraft would have a worse performance in this area. The fact of transporting less number of passengers with a little reduction in the price that costs transporting that passengers it is not profitable. In fact, it is significantly more expensive, with an increase of the price near the 11%. For this reason, the *BAe 146-100* is better than the *E-FAN X* in this area.

Taking into account the reduction of passengers, looking at Table 4.17 and 4.18 and Figures 4.4 and 4.5, it can be seen that the route with the less DOC per seat mile is the route Hamburg - Rome. This route then shall be selected for the commercial utilization of the aircraft, due to it is the route that generates the less expenses per seat and mile. The percentage difference for this route between both aircraft is $(0.42984 - 0.38280)/0.38280\ \% = 12.288\%$. For the same route, the *E-FAN X* has a value of DOC per seat 12.288% higher. This makes the new aircraft completely less competitive in the commercial area than the old aircraft.

**Table 4.14** DOC comparison for the Hamburg - Prague route

| Hamburg - Prague | | | |
|---|---|---|---|
| USD | *BAe 146-100* | *E-FAN X* | Percentage difference |
| Depreciation | 3139982 | 3177748 | 1.203 |
| Interest | 2582950 | 2614016 | 1.203 |
| Insurance | 212389 | 214649 | 1.064 |
| Fuel | 4341200 | 4289440 | -1.192 |
| Maintenance | 5559074 | 5559074 | 0 |
| Staff | 3714583 | 3714583 | 0 |
| Fees and charges | 8497265 | 8054192 | -5.214 |
| TOTAL | 28047446 | 27623702 | -1.511 |
| $n_{pax,X}$ | 82 | 73 | |
| Range (NM) | 311 | 311 | |
| Fights per year | 2050 | 2050 | |
| DOC per seat mile | 0.53649 | 0.59353 | 10.651 |

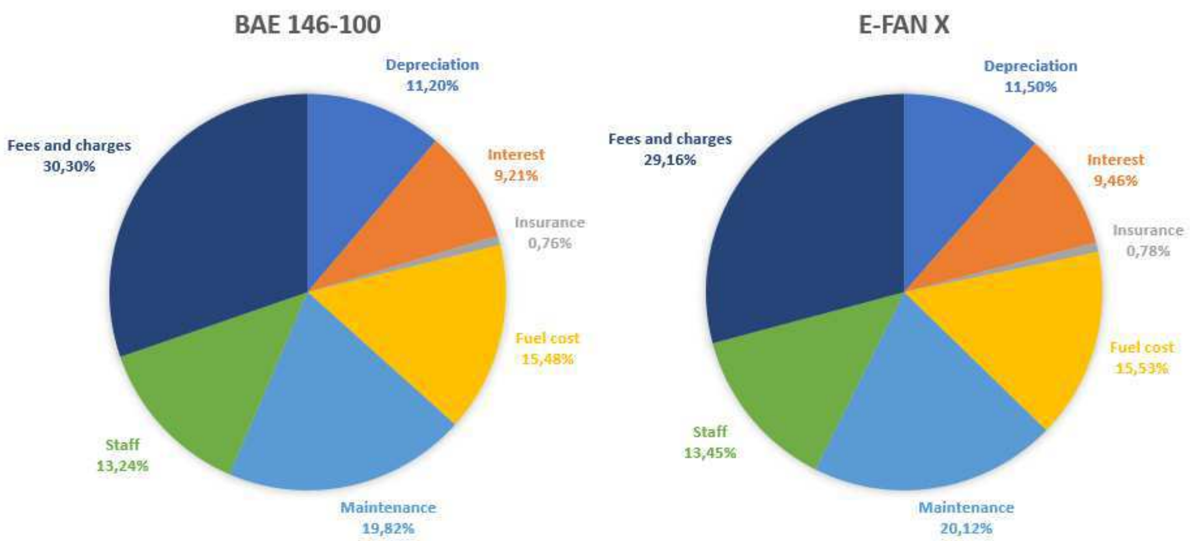


**Figure 4.1** DOC percentage for the route Hamburg - Prague

**Table 4.15** DOC comparison for the Hamburg - Paris route

| Hamburg - Paris | | | |
|---|---|---|---|
| USD | *BAe 146-100* | *E-FAN X* | Percentage difference |
| Depreciation | 3139982 | 3177748 | 1.203 |
| Interest | 2582950 | 2614016 | 1.203 |
| Insurance | 212389 | 214649 | 1.064 |
| Fuel | 4405920 | 4356080 | -1.131 |
| Maintenance | 5387420 | 5387420 | 0 |
| Staff | 3911915 | 3911915 | 0 |
| Fees and charges | 8709811 | 8329849 | -4.362 |
| TOTAL | 28350387 | 27991677 | -1.265 |
| $n_{pax,X}$ | 82 | 73 | |
| Range (NM) | 472 | 472 | |
| Fights per year | 1758 | 1758 | |
| DOC per seat mile | 0.41666 | 0.46210 | 10.908 |

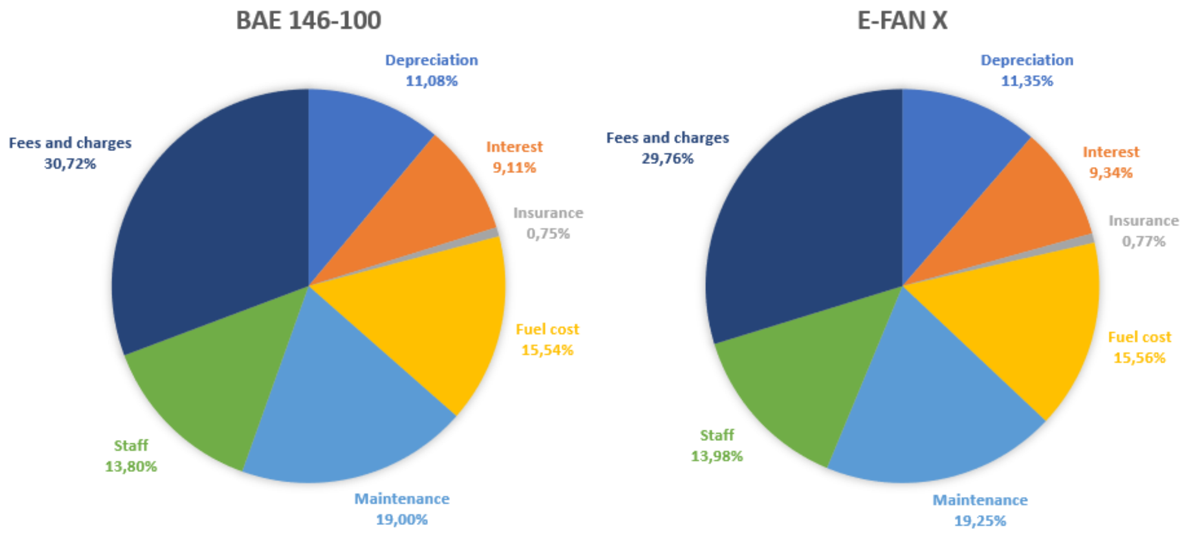


**Figure 4.2** DOC percentage for the route Hamburg - Paris

**Table 4.16** DOC comparison for the Hamburg - Marseilles route

| Hamburg - Marseilles | | | |
|---|---|---|---|
| USD | *BAe 146-100* | *E-FAN X* | Percentage difference |
| Depreciation | 3139982 | 3177748 | 1.203 |
| Interest | 2582950 | 2614016 | 1.203 |
| Insurance | 212389 | 214649 | 1.064 |
| Fuel | 4488400 | 4440720 | -1.062 |
| Maintenance | 5193829 | 5193829 | 0 |
| Staff | 4138126 | 4138126 | 0 |
| Fees and charges | 8959389 | 8621184 | -3.775 |
| TOTAL | 28685065 | 28400272 | -0.992 |
| $n_{pax,X}$ | 82 | 73 | |
| Range (NM) | 733 | 733 | |
| Fights per year | 1426 | 1426 | |
| DOC per seat mile | 0.33467 | 0.37220 | 11.214 |

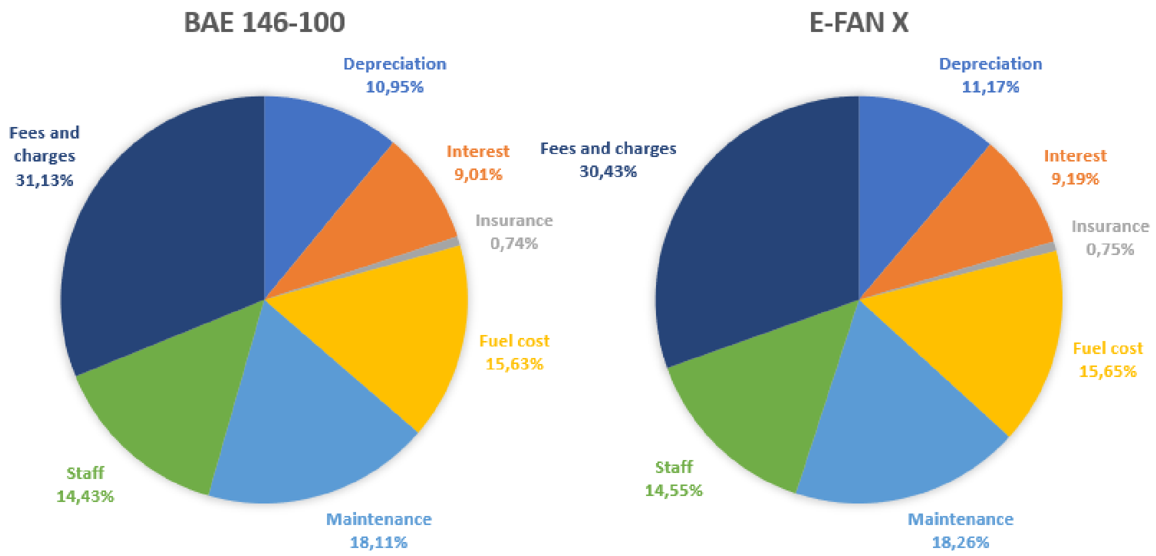


**Figure 4.3** DOC percentage for the route Hamburg - Marseilles

**Table 4.17** DOC per seat mile for the *BAe 146-100* for different routes

| | *Bae 146-100* | | | | | |
|---|---|---|---|---|---|---|
| From Hamburg to | Prague | Paris | Marseilles | Rome | Barcelona | Madrid |
| Range (NM) | 311 | 474 | 736 | 829 | 930 | 1122 |
| DOC (USD) | 28047446 | 28350387 | 28685065 | 28826618 | 28874745 | 29063702 |
| $n_{pax,X}$ | 82 | | | | | |
| DOC per seat mile | 0.53649 | 0.41666 | 0.33467 | 0,31646 | 0,302908 | 0.28280 |
| Real $n_{pax}$ | 82 | 82 | 71 | 68 | 63 | 56 |
| Real DOC per seat mile | 0.53640 | 0.41659 | 0.38640 | 0.38280 | 0.39524 | 0.41542 |

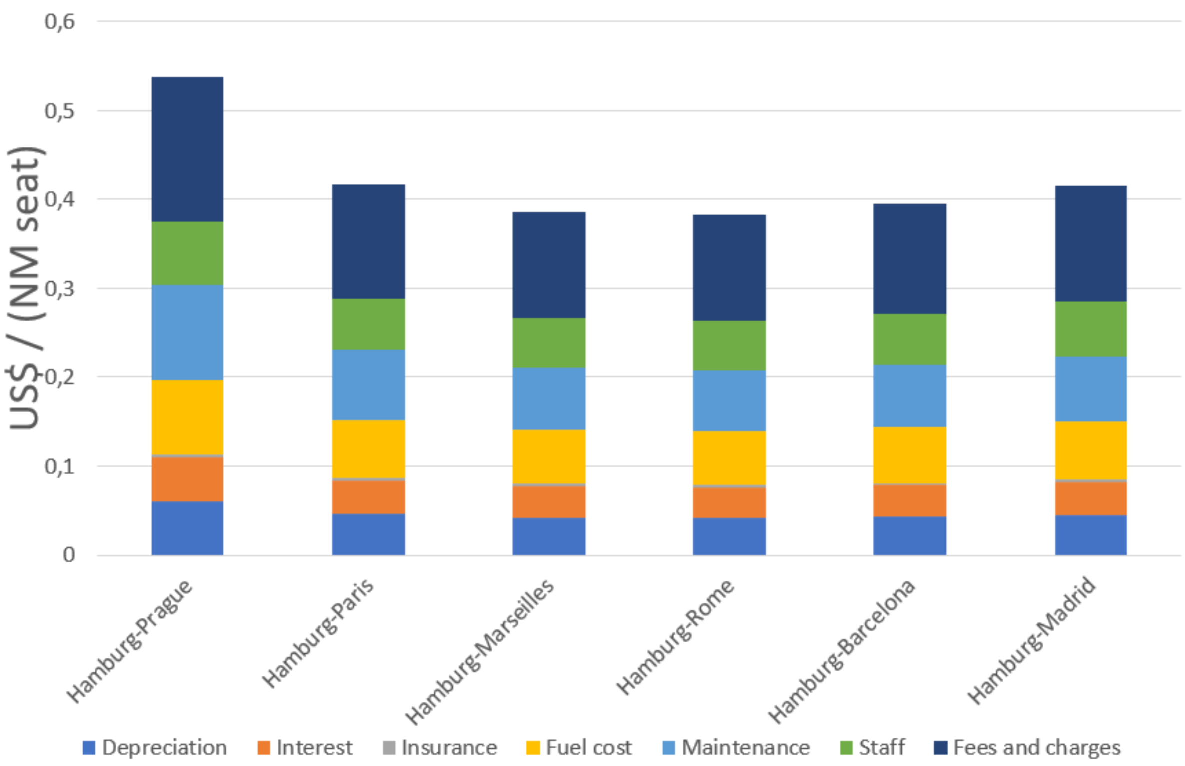


**Figure 4.4** DOC per seat mile for the *BAe 146-100* with the real $n_{pax,X}$

**Table 4.18** DOC per seat mile for the *E-FAN X* for different routes

| | *E-FAN X* | | | | | |
|---|---|---|---|---|---|---|
| From Hamburg to | Prague | Paris | Marseilles | Rome | Barcelona | Madrid |
| Range (NM) | 311 | 474 | 736 | 829 | 930 | 1122 |
| DOC (USD) | 27682151 | 28043270 | 28444050 | 28602604 | 28668660 | 28883728 |
| $n_{pax,X}$ | 73 | | | | | |
| DOC per seat mile | 0.593535 | 0.46210 | 0.36774 | 0,34903 | 0,33408 | 0,31242 |
| Real $n_{pax}$ | 73 | 73 | 63 | 60 | 56 | 48 |
| Real DOC per seat mile | 0.59353 | 0.46210 | 0.43115 | 0.42984 | 0.44085 | 0.48104 |

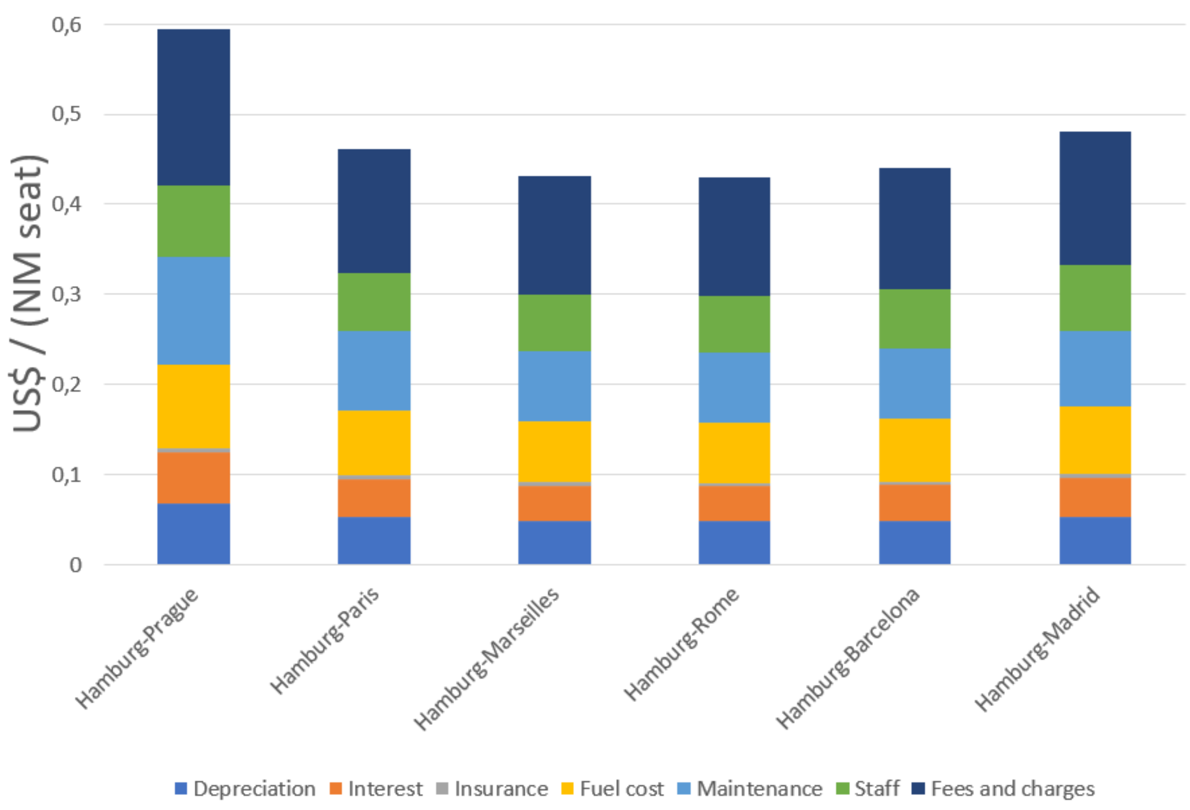


**Figure 4.5** DOC per seat mile for the *E-FAN X* with the real $n_{pax,X}$

All the results and comparisons shown before correspond to the objective assessment of the economic area. But there are some parameters that could bring an added value to the the airline. Aspects like performance, operating flexibility, commonality or comfort, become important to reach a competitive position. All the different parameters have been studied in Nita (2012). Figure 4.6 shows all the parameters involved in the studio. The performance of both aircraft is the same, so no changes are produced in this area. It is the same for the cargo handling. The possible changes can come then from the passenger comfort. But the features of the seats are not changed in both configurations. It only changes the number of seats of first and economic class. There are then no differences in the added value between both aircraft. The DOC results shown before are then a good estimation of the economical differences that both aircraft have.

| | | | | | | | | | | | | **Absolute weights** | **Added Values scaled to 100 %** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Economics | 75 | % | Equiv. ton-mile costs | 100 | % | | | % | | | % | 75.00% | |
| Added Values | 25 | % | Performance | 35 | % | Airport performance | 50 | % | Landing field length | 0 | % | 0.00% | 0.00% |
| | | | | | | | | | Take-off field length | 80 | % | 3.50% | 14.00% |
| | | | | | | | | | Relative landing weight ($m_{ML}/m_{MTO}$) | 20 | % | 0.88% | 3.50% |
| | | | | | | Cruise performance | 50 | % | Cruise speed | 100 | % | 4.38% | 17.50% |
| | | | Passenger Comfort | 55 | % | Concerning all passengers | 80 | % | Seat pitch | 30 | % | 3.30% | 13.20% |
| | | | | | | | | | Seat width | 20 | % | 2.20% | 8.80% |
| | | | | | | | | | Armrest width | 10 | % | 1.10% | 4.40% |
| | | | | | | | | | Aisle width | 5 | % | 0.55% | 2.20% |
| | | | | | | | | | Aisle height | 5 | % | 0.55% | 2.20% |
| | | | | | | | | | Overhead bin volume per pax | 20 | % | 2.20% | 8.80% |
| | | | | | | | | | Aircraft gust sensibility | 10 | % | 1.10% | 4.40% |
| | | | | | | Concerning part of the passengers | 20 | % | Sidewall clearance | 10 | % | 0.28% | 1.10% |
| | | | | | | | | | Number of "excuse-me" seats | 90 | % | 2.48% | 9.90% |
| | | | Cargo Handling | 10 | % | Concerning cargo | 80 | % | Containerized cargo (yes/no) | 100 | % | 2.00% | 8.00% |
| | | | | | | Concerning cargo working conditions | 20 | % | Accessibility factor | 50 | % | 0.25% | 1.00% |
| | | | | | | | | | Cargo compartment height | 50 | % | 0.25% | 1.00% |
| | | | | | | | | | | | Check: | 100.00% | 100.00% |

**Figure 4.6** Added value by Nita (2012)

# 5 Environmental Analysis

The ambitious project of the *E-FAN X* consists in the replacement of one of the four *Lycoming ALF 502R-5* engines of the *BAe 146-100* with the *AE 2100A* turboshaft. This generates some differences in the features of the aircraft, that has been explained in Chapter 3. The difference performance of the engines and the distinct number of passengers generates differences in the economic area, but also in the environmental area. The distinct features of the engines supposes differences in the quantity of the emissions. But also the different number of passenger makes that this differences in emissions are shared with a different number of people. All this effects need to be measured and studied, in order to establish the environmental impact of the new aircraft. It is necessary to do the study of both aircraft, in order to do the comparison. In this way, it can be affirmed if the *E-FAN X* is more eco-friendly than the *BAe 146-100* or not.

The way of analyze the environmental impact is with a Life-cycle assessment method. LCA is a technique to assess environmental impacts associated with all the stages of a life of a product from raw material extraction through materials processing, manufacture, distribution, use, repair, maintenance, and disposal or recycling. This assessment is not a risk evaluation, due to the LCA only quantify the amount of emissions. The real impact of the emissions depends on when, where, and how the emissions are released to the environment. The phases of a LCA are four: goal and scope, life cycle inventory, life cycle impact assessment and interpretation. In this master thesis it is not necessary to develop the four phases, it is just necessary to analyze the life cycle impact assessment. Thus, the comparison of both aircraft is achieved.

There are so many different phases in the life cycle of the aircraft. But because it is only required to do the comparison between both aircraft, it is only necessary then to pay attention to the differences that both aircraft have. And the reality is that the only distinction between both aircraft is the different engine. It means that the airframe is the same. Then, it is not necessary to analyze the impact of the life cycle for the airframe. The impact is the same for both aircraft. The different engines will generate a different impact in the life cycle, from the extraction of the material to the disposal of the aircraft. But this differences can be taken as negligible, due to the dimension of the engines in comparison with the whole aircraft. The main dissimilarities for the engines come from their difference performance. This difference performance generates a different amount of emissions during all the operative life of the aircraft. And for this reason the emissions are the effect that has been study in this master thesis.

Regardless the emission calculation done, what it is necessary to take into account is the different number of seats that both aircraft have. The total amount of pollution is going to be divided by a different number of passengers. But it is also important to take into account the distinct number of seats per class. Both aircraft have two classes, and dissimilar number of seats per class for the same class. To do a good comparison, it can be calculated the total amount of emissions of the aircraft, and then obtain the relative emission per seat of class. For this purpose it is necessary to obtain the total surface occupied by the seats in both configuration. The area required for the first class is higher than the area for the low class, although they both count as one seat. It means that one seat of first class is more pollutant than one seat of economic class. That is the reason to use the percentage surface occupied for each class. The total amount of emissions can be then related to one percentage of surface, that is also attached to a certain number of seats. Thus, a correlation of the emission per seat of class can be done between both aircraft, using the data of Table 3.14 in Chapter 3. The emission per seat class of one element would be in this way

$$\frac{Emission}{seatclass} = \frac{surface\ occupied\ by\ the\ class}{total\ surface\ occupied\ by\ all\ the\ seats} \cdot \frac{total\ mass\ emited}{number\ of\ seats\ of\ the\ class} \tag{5.1}$$

Before starting with the environmental study, it is important to explain how the combustion of the fuel works. The fuel used in the commercial aviation is the jet fuel. This kind of combustible releases carbon dioxide ($CO_2$), water vapor ($H_2O$) and sulfur oxides ($SO_x$) in an ideal combustion. But the real combustion of the fuel generates, besides the products stated above, also pollutants as nitrogen oxides ($NO_x$), carbon monoxide ($CO$), unburned hydrocarbons ($HC$) and soot, as it shows Figure 5.1.

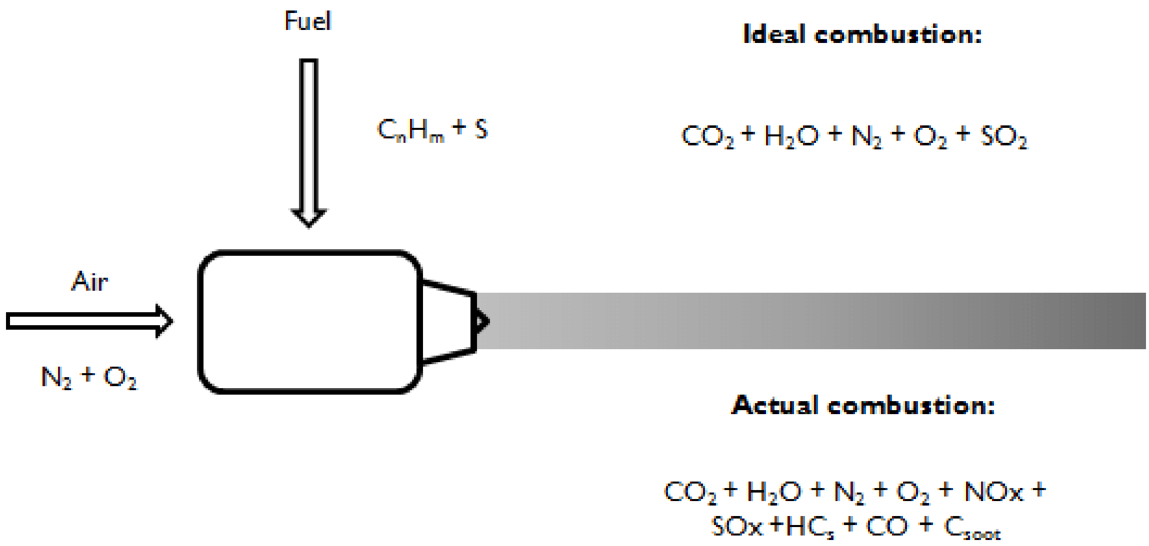


**Figure 5.1** Scheme of the jet fuel combustion (Timmis 2015)

The nitrogen and oxygen that the combustion releases are already part of the atmosphere. They represent between 91.5% and 92.5% of the emission products. So only the remaining percentage is the culprit of the environmental impact. Between the 7% and 8% of the emissions are carbon dioxide and water vapor, and about 0.5% corresponds to sulfur dioxide, unburned hydrocarbons, carbon monoxide, nitrogen dioxide and soot particles (Sarkar 2012).

The emissions of some products are directly appraised to the fuel consumption. This means that the amount of mass emitted of the product is proportional to the fuel burned, regardless the operation mode of the engine. This occurs with the $CO_2$, $H_2O$, $SO_x$ and soot. The emissions index of this products are gathered in Table 5.1. The EI corresponds to the kilograms of product released with the combustion of one kilogram of jet fuel.

The emission of the other products depends on the combustion efficiency of the engine, but also on the mode of operation and the thrust settings. Is then necessary to know the performance of the engines in depth to make the assessment. For this reason, it has been used the Engine

**Table 5.1** Emission indices of emission products (IPCC 1999)

| Products | Emission Index (kg/kg fuel) |
|---|---|
| $CO_2$ | 3.16 |
| $H_2O$ | 1.23 |
| $SO_2$ | $2 \cdot 10^{-4}$ |
| Soot | $4 \cdot 10^{-4}$ |

Emissions Databank given by EASA (2017). The ICAO Engine Emissions Databank is a voluntary database for engine manufactures. They provide information about the exhaust emissions tests of their engines in the Landing and Take Off cycle. This information is collected in one database which is hosted by the European Aviation Safety Agency on behalf of ICAO. It has to be mentioned that in this databank it can be found the information about the *Lycoming ALF 502R-5* but not the information about the *AE 2100A*. In fact, it is not possible to know the data for this engine. Then is not possible to know the emissions for this engine. But it is possible to set an upper limit of the emissions that the *AE 2100A* shall have if the new configuration wants to be more eco-friendly than the old configuration.

When studying the emissions, it is important to be aware of the flight phase that it is being analyzed. During the flight phases close to the airport, the most important studies are about the particles that have a potential bad effect on the human health, and the impact of the noise in the surroundings of the airport. But during the cruise phase, the studies shall take into account the particles that contributes to the global change, and the comfort of the passengers due to the noise of the aircraft. For this reason, the assessment has been divided in three different areas:

- Local air quality
- Climate impact
- Noise pollution

## 5.1 Local Air Quality

This subsection focus on the emissions produced in the surroundings of the airports. In order to allow the comparison of the measurements for different aircraft, and to provide a standardization, a reference procedure was defined. This procedure is called the Landing and Take Off Cycle. The LTO includes every flight phase of the aircraft below 3000 ft. That is the taxi out, take off, climb out, final approach, and taxi in, as it shows Figure 5.2.

For this test, the thrust and time required for each phase are fixed, as it can be seen in Table 5.2. This allows to obtain the mass of fuel burned during each phase. Therefore, it is easy to calculate the emitted mass of the different species by multiplying the amount of mass fuel burned by the EI of each specie. The mass of the specie $x$ is then obtained with Equation 5.2.

$$m_{x,p} = T_{TO}\eta_p t_p TSFC_p EI_{x,p} \tag{5.2}$$

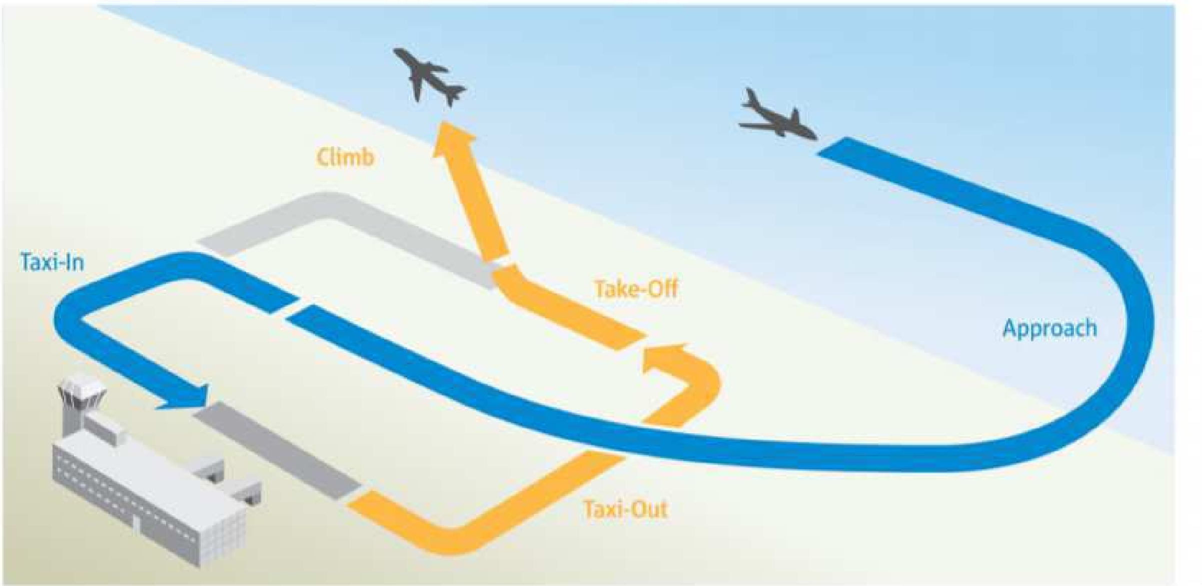


**Figure 5.2** Landing and take off cycle definition (ICAO 2008).

Where $p$ represents de flight phase, $\eta$ represents the percentage of thrust required for the flight phase, and $t$ represents the time required for the flight phase. The EI depends on the element is being analyzed but also the flight phase. For the value of the TSFC it has been made one assumption. During the take off and climb out phases, the $TSFC$ corresponds to the $TSFC_{TO}$. During the approach, taxi out and taxi in it corresponds to the $TSFC_{CR}$. It is necessary to make this distinction, because these flight phases are completely different, and need to be analyzed in a different way. The assumption that the $TSFC$ for the take off and climb out is the $TSFC_{TO}$ is completely valid, due it is similar to the reality. But for the taxi in, taxi out and approach the value of the $TSFC$ it is not exactly the $TSFC_{CR}$. As no more data is known for the engine, this assumption has been realized in this study, in order to take into account the difference $TSFC$ of the different flight phases.

**Table 5.2** Thrust and operating time for each flight phase (ICAO 2008)

| Flight phase | Thrust (%) | Time (min) | TSFC (kg/Ns) |
|---|---|---|---|
| Taxi out | 7 | 7 | $2.170 \cdot 10^{-5}$ |
| Take off | 100 | 0.7 | $1.154 \cdot 10^{-5}$ |
| Climb out | 85 | 2.2 | $1.154 \cdot 10^{-5}$ |
| Approach | 30 | 4 | $2.170 \cdot 10^{-5}$ |
| Taxi in | 7 | 19 | $2.170 \cdot 10^{-5}$ |

During the LTO, the worst type of emissions are the emissions that can harm the well-being of humans as well as the balance of fauna and flora. This types of emissions are the emissions required to study. The health problems are mostly caused by inhaling particles and Ozone. Once the particles enter the human body through the respiratory system, diseases such as cancer and respiratory infections can be developed. Two types of Particulate Matter are distinguished. Primary PM is defined as the particles that are directly emitted into the air due to the engine performance. When the particles are formed through a chemical reaction of gaseous pollutants that come from the emissions of the engine, it is defined as secondary PM (WHO 2014).

To determine a metric for the local air quality, it has been used the *ReCiPe* method (RVIM 2016). The *ReCiPe* is a method for the impact assessment in a LCA. It translates emissions and resource extractions into a limited number of environmental impact scores by means of characterization factors. Because the local air quality focuses on the human health in the vicinity of the airport, the metric of the evaluation of the local air quality will consist in $NO_x$ emissions, Non-Methane Volatile Organic Compound or Ozone formation potential equivalents (NMVOC) and PM equivalents. The emissions of $NO_x$ are known thanks to the Engine Emisssion Databank, but the other two factors are calculated by converting relevant emissions products. For this purpose, in Table 5.3 are listed the characterization factors employed.

**Table 5.3** Characterization factors of *ReCiPe* (RVIM 2016)

| | $NO_x$ | $SO_2$ | PM | CO | HC |
|---|---|---|---|---|---|
| Photo-chemical oxidant formation (Ozone) | 1 | 0.081 | - | 0.046 | 0.476 |
| Particulate matter formation | 0.11 | 0.29 | 1 | - | - |

### 5.1.1 $NO_x$ Emissions

The EI for the $NO_x$ is given for each flight phase in the Engine Emission Databank for the *ALF 502R-5*. In order to obtain the total amount of $NO_x$ emitted in each flight phase it is necessary to use Equation 5.2. The value of $NO_x$ mass emitted is shown in Table 5.4.

**Table 5.4** Total amount of $NO_x$ emitted during the LTO (EASA 2017)

| Flight phase | EI $NO_x$ (g/kg fuel) | $NO_x$ mass (g) |
|---|---|---|
| Taxi out | 3.78 | 74.76 |
| Take off | 13.35 | 200.69 |
| Climb out | 10.56 | 424.10 |
| Approach | 6.6 | 319.67 |
| Taxi in | 3.78 | 202.92 |
| | TOTAL $NO_x$ mass | 1222.14 |

It is possible to obtain the mass of $NO_x$ emitted per seat class using the layout of the *BAe 146-100* listed in Table 3.14. It is just necessary to relate the total mass of $NO_x$ emitted with the relative surface that each class have, as explained in Equation 5.1. The $NO_x$ emissions per seat can be obtained in this way, and the results are shown in Table 5.5.

**Table 5.5** Emissions of $NO_x$ per seat class for the *BAe 146-100*

| Seat class | Number of seats | Percentage of total surface (%) | $NO_x$ per seat (g/seat) |
|---|---|---|---|
| First class | 12 | 19.12 | 19.47 |
| Economic class | 70 | 80.88 | 14.12 |

As mentioned before, the emissions for the *E-FAN X* are not known. But if this aircraft want to have a better performance in this area, it should have less emissions per seat than the *BAe 146-100*. Then, a limit on the emissions for the new configuration can be calculated, establishing as upper limit the emissions released by the previous configuration. This means that the *E-FAN X* shall have, as upper limit, the same emissions per seat class than the *BAe 146-100*. With this requirement, the total limit amount of $NO_x$ released is calculated in Table 5.6.

**Table 5.6** Upper limit of emissions of $NO_x$ for the *E-FAN X*

| Seat class | $NO_x$ per seat (g/seat) | Number of seats | Mass of $NO_x$ (g) |
|---|---|---|---|
| First class | 19.47 | 3 | 58.41 |
| Economic class | 14.12 | 70 | 988.40 |
| | TOTAL $NO_x$ mass | | 1046.81 |

The reduction in the $NO_x$ emissions shall be $(1046.81-1222.14)/1222.14\ \% = -1.35\%$. And this must be achieved only with the difference performance of one engine. For the old configuration, all the engines contributes the same to the $NO_x$ emissions, which means an emission of $1222.14/4 = 305.54$ g $NO_x$/engine. The new engine must provide then $1046.81-3\cdot 305.54 = 130.19$ g $NO_x$, which represents a percentage different of $(130.19-305.54)/305.54\ \% = -57.39\%$. The *AE 2100A* must have a reduction in the $NO_x$ emissions of $-57.39\%$ in order to have at least the same emissions per seat class than the old configuration. This difference is huge, and it is predictably not going to be achieved by the *AE 2100A*. This means that probably the new performance is going to be worse in the $NO_x$ emission scenario.

### 5.1.2 Ozone Emission

For the Ozone emissions, the total amount of Ozone equivalents can be calculated with Equation 5.3 by multiplying the total emitted mass of the relevant emission products by their corresponding factor given in Table 5.3. There are too many chemical products that contributes to the Ozone formation. This means that the Equation 5.3 shall have a longer list of terms. But in order to simplify, it has been used the approach given by Van Endert (2017). In this way the Ozone formation depends on the emission of $NO_x$, $SO_2$, $CO$ and $HC$. The EI for the $CO$ and $HC$ are shown in the Table 5.7. For the $SO_2$, its value depends only on the thrust-specific fuel consumption, and its given in the Table 5.1. Using this values, the total mass of Ozone released is gathered in Table 5.9

$$NMVOC = 1\cdot NO_x + 0.081\cdot SO_2 + 0.046\cdot CO + 0.476\cdot HC \tag{5.3}$$

**Table 5.7** EI for the $CO$ and $HC$ (EASA 2017)

| Flight phase | CO (g/kg fuel) | HC (g/kg fuel) |
|---|---|---|
| Taxi out | 40.39 | 5.39 |
| Take off | 0.300 | 0.060 |
| Climb out | 0.250 | 0.053 |
| Approach | 7.1 | 0.217 |
| Taxi in | 40.39 | 5.39 |

**Table 5.8** Total amount of Ozone emitted for each product during the LTO

| Ozone due to | $NO_x$ (g) | $SO_2$ (g) | CO (g) | HC (g) | Total Ozone (g) |
|---|---|---|---|---|---|
| Taxi out | 74.76 | 0.32 | 36.75 | 50.74 | 162.57 |
| Take off | 200.69 | 0.24 | 0.21 | 0.43 | 201.57 |
| Climb out | 424.10 | 0.65 | 0.46 | 1.01 | 426.22 |
| Approach | 319.67 | 0.78 | 15.82 | 5.00 | 341.27 |
| Taxi in | 202.92 | 0.87 | 99.74 | 137.72 | 441.25 |
| | TOTAL Ozone mass | | | | 1572.88 |

It can be appreciated that the $NO_x$ is the emission with more weight for the formation of Ozone, followed by the $HC$. The $CO$ have less influence, and the $SO_2$ has almost a negligible influence. The emissions per seat class of the *BAe 146-100* are listed in Table 5.9. Following the earlier idea, the limit emissions of Ozone per seat that the *E-FAN X* shall have are the emissions per seat class that the *BAe 146-100* have. Taking into account the different number of seats for each class, and the dissimilar surface, the Ozone upper limit mass emitted by the *E-FAN X* is shown in the Table 5.10.

**Table 5.9** Emissions of Ozone per seat class for the *BAe 146-100*

| Seat class | Number of seats | Percentage of total surface (%) | Ozone per seat (g/seat) |
|---|---|---|---|
| First class | 12 | 19.12 | 25.06 |
| Economic class | 70 | 80.88 | 18.17 |

The reduction in emissions shall be $(1347.08 - 1572.88)/1572.88\ \% = -14.36\%$. Only one engine is in charge to achieve this reduction. Each engine in the old configuration produce $1572.88/4 = 393.22$ g/engine, so the new engine must provide $1347.08 - 3 \cdot 393.22 = 167.48$ g. The reduction in Ozone emissions shall be then $(167.48 - 393.22)/393.22\ \% = -57.41\%$. Again, the estimated reduction imposed for the *AE2100A* is so demanding. It is foreseeable that the performance of the new configuration is going to be worse in this scenario too.

**Table 5.10** Upper limit of Ozone emissions for the *E-FAN X*

| Seat class | Ozone per seat (g/seat) | Mass of ozone produced (g) |
|---|---|---|
| First class | 25.06 | 75.18 |
| Economic class | 18.17 | 1217.90 |
| | TOTAL Ozone mass | 1347.08 |

### 5.1.3 Particulate Matter

The total mass emitted is calculated with the equivalent Particulate Matter. It is necessary to use the characterization factors of the *ReCiPe* method. The Equation 5.4 shows that the main responsible are the $NO_x$, the $SO_2$ and the volatile and non-volatile PM.

$$PM_{equivalent} = 0.11 \cdot NO_x + 0.29 \cdot SO_2 + PM_{vols} + PM_{nvols} \tag{5.4}$$

The values for the $NO_x$ and the $SO_2$ are known for the LTO (Table 5.9), but not the volatile and non-volatile PM. For this reason, and to keep using the Engine Emission Databank, it has been used the method described in Wayson (2009).

The volatile PM are directly related to the emission of $SO_2$ and $HC$. Following the rules described in Wayson (2009), the relation is

$$PM_{vols} = 0.033 \cdot SO_2 + 0.0085 \cdot HC \quad . \tag{5.5}$$

For the non-volatile PM, the estimation is more complicated, and involve more factors. The total mass emitted can be obtained with the Equation 5.6.

$$PM_{nvols,i} = Q_i \cdot 0.0694 \cdot SN_i^{1.24} \cdot wf_i \cdot t_i \tag{5.6}$$

Where $i$ describes the operating mode of the LTO, $Q$ the exhaust volumetric flow rate, $SN$ the smoke number, $wf$ the fuel flow in kilograms per seconds and $t$ the time for the operating mode. The values of $SN$ and $wf$ are given in the Engine Emission Databank, and the time of each mode is already definde in the LTO. It only remains to know the exhaust volumetric fuel flow. For a turbofan, this value depends on the Air to Fuel Ratio (AFR) as follows

$$Q = 0.776 \cdot AFR + 0.887 \quad . \tag{5.7}$$

The values of the AFR are also given in Wayson (2009), so the values of the volumetric fuel flow can be obtained. As all the data for the non-volatile PM is known, in Table 5.11 can be seen the contribution of each flight phase and the total mass emitted.

**Table 5.11** Total amount of non-volatile PM emitted during the LTO (Wayson 2009)

| Flight phase | AFR | Q ($m^3$/kg fuel) | SN | wf (kg/s) | $PM_{nvols}$ mass (g) |
|---|---|---|---|---|---|
| Taxi out | 106 | 83.1 | 2.3 | 0.0408 | 277.60 |
| Take off | 45 | 35.8 | 13.5 | 0.3581 | 942.13 |
| Climb out | 51 | 40.5 | 12.7 | 0.2955 | 2562.49 |
| Approach | 83 | 65.3 | 5.7 | 0.1034 | 973.40 |
| Taxi in | 106 | 83.1 | 2.3 | 0.0408 | 753.47 |
| | TOTAL $PM_{nvols}$ mass | | | | 5509.09 |

To determine the volatile PM, it can be used the information gathered in Table 5.9 about the emission of this to species. The volatile PM is listed in Table 5.12.

**Table 5.12** Total amount of volatile PM emitted during the LTO

| Flight phase | $SO_2$ | $NO_x$ | $PM_{vols}$ mass (g) |
|---|---|---|---|
| Taxi out | 0.13 | 0.04 | 0.17 |
| Take off | 0.10 | 0.0051 | 0.1051 |
| Climb out | 0.27 | 0.0045 | 0.2745 |
| Approach | 0.32 | 0.0018 | 0.3218 |
| Taxi in | 0.35 | 0.046 | 0.396 |
| | TOTAL $PM_{nvols}$ mass | | 1.2674 |

The total PM can be obtained (Table 5.13), and also the mass of PM per seat class for the *BAe 146-100* (Table 5.14), that has to be the same for the *E-FAN X* if it wants to be as eco-friendly as the original aircraft. The total mass of PM released by the *E-FAN X* is shown in Table 5.15.

The reduction in PM mass emission shall be $(4844.10-5655.05)/5655.05\ \% = -14.34\%$, but only one engine is the responsible to achieve this difference. One old engine produces $5655.05/4 = 1413.76$ g/engine, so the new engine must release $4844.10-3\cdot 1413.76 = 602.82$ g, which means a reduction in the emissions of $(602.82-1413.76)/1413.76\ \% = -57.36\%$. The reduction is so demanding if the new configuration wants to be as eco-friendly as the old configuration in this area.

**Table 5.13** Total amount of PM emitted for each product during the LTO

| PM due to | $PM_{nvols}$ (g) | $PM_{vols}$ (g) | $NO_x$ (g) | $SO_2$ (g) | Total PM mass (g) |
|---|---|---|---|---|---|
| Taxi out | 277.60 | 0.17 | 8.22 | 1.15 | 287.14 |
| Take off | 942.13 | 0.1051 | 22.08 | 0.87 | 965.19 |
| Climb out | 2562.49 | 0.2745 | 46.65 | 2.33 | 2611.74 |
| Approach | 973.40 | 0.3218 | 35.16 | 2.80 | 1011.68 |
| Taxi in | 753.47 | 0.396 | 22.32 | 3.11 | 779.30 |
| | TOTAL PM mass | | | | 5655.05 |

**Table 5.14** Emissions of PM per seat class for the *BAe 146-100*

| Seat class | Number of seats | Percentage of total surface (%) | PM per seat (g/seat) |
|---|---|---|---|
| First class | 12 | 19.12 | 90.10 |
| Economic class | 70 | 80.88 | 65.34 |

**Table 5.15** Upper limit of PM emissions for the *E-FAN X*

| Seat class | PM per seat (g/seat) | Mass of PM produced (g) |
|---|---|---|
| First class | 90.10 | 270.30 |
| Economic class | 65.34 | 4573.80 |
| | TOTAL PM mass | 4844.10 |

## 5.2 Climate Impact

The cruise phase is the flight phase that takes more time in the performance of the aircraft. During this period of time, the aircraft generates some emissions that are deposited directly into the upper troposphere and lower stratosphere, leading to more effective ozone production and the formation of contrail and cirrus clouds. To do an study of the climate impact of this flight phase, it is necessary first off all to establish a metric to asses the climate impact, in order to realize which components are implicated the most in the climate change. There are several ways to analyze the climate impact, but the most used typically is the Radiative Forcing. This parameter represents how the radiation balance of the earth is affected by a specific gas or particles by defining the amount of absorbed energy in the earths system as well as the energy that is radiated back into space. This causes a change in the global temperature. An augmentation in the temperature occurs by a positive RF value and a reduction by a negative value. The RF value is expressed in units of Watts per square meter. It can be seen in Figure 5.3 the RF caused by the distinct pollutants generated by the aviation since the beginning of the jet era until 2005. The black bars represent the possible deviation of the value due to unknown effects and unknown parameters. It can be appreciated that the the total RF of aviation is mostly determined by the $CO_2$ emissions, $NO_x$ emissions and contrails and cirrus clouds. Therefore those three types of emissions are going to be analyzed in this section.

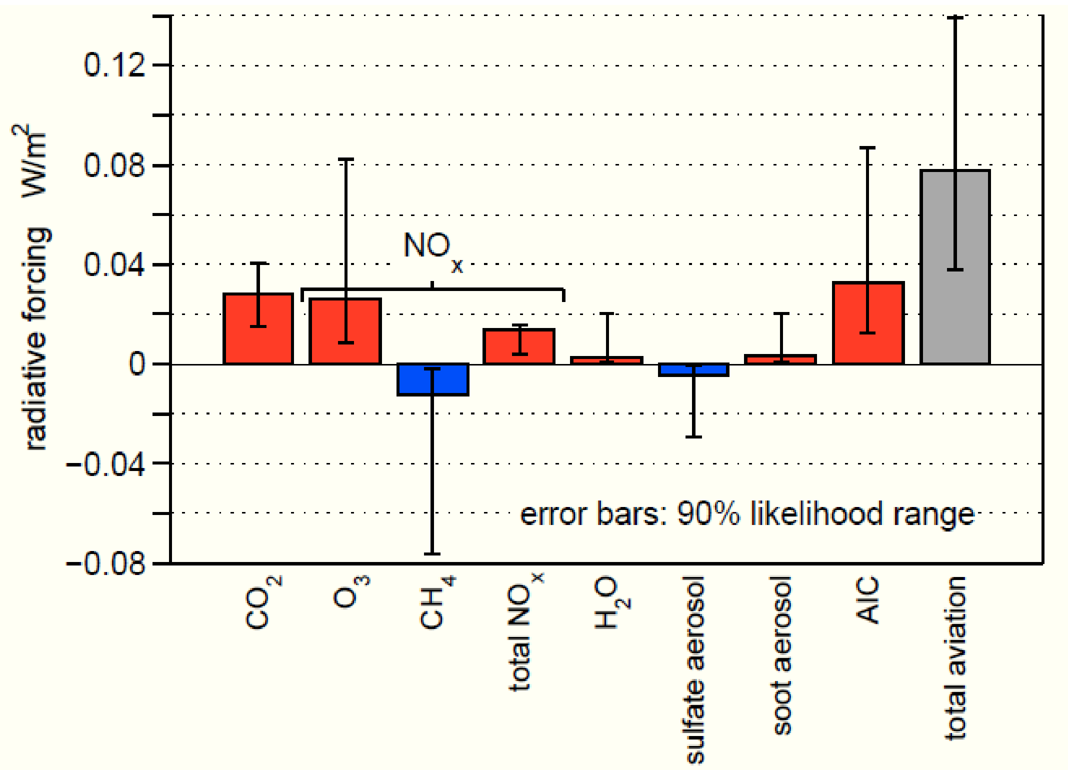


**Figure 5.3** RF in 2005 due all aircraft previous emissions (Schwartz 2011, reprinted from Lee 2009)

The effects of the cirrus and contrails are not well known yet by the scientific community. Regarding the $NO_x$, it participates in the Ozone formation, which effects are known, and also in the $CH_4$ formation, which effects are not good known. This generates some uncertainty in the $NO_x$ study. The only effects well known are the effects caused by the $CO_2$. This fact also can be appreciated looking at the deviation of the black bars of Figure 5.3. The $CO_2$ RF is the value with the less percentage deviation. For this reason it is a good idea to use one method that compares all the possible emissions with the emissions of $CO_2$. Following the idea of the RF, another metric is going to be used, called Global Warming Potential. The GWP method determines the severity of the influence of certain emission products on climate impact compared to $CO_2$ over a certain time interval, mostly 100 years also referred as carbon dioxide equivalent. Therefore, the time-integrated RF of the non $CO_2$ species is normalized by the time-integrated RF of $CO_2$ over the same time interval. This integrate can be done assuming maintained emissions or pulse. This GWP method is used in the *ReCiPe* LCA. If it is required to calculate the equivalent $CO_2$ emissions due to this three components it is necessary to use Equation 5.8. Following the method developed by Van Endert (2017), the equation is

$$CO_{2,equiv} = E_{i,CO_2} \cdot 1 + E_{i,NO_x} \cdot CF_{midpoint,NO_x} + L \cdot CF_{midpoint,clouds} \quad . \tag{5.8}$$

To obtain the mass of $CO_2$ and $NO_x$ consumed is necessary to resort to the EI of each specie and the fuel consumed during the trip (Equation 5.9). For the $CO_2$ its value is directly proportional to the fuel consumed (Table 5.1). But for the value of $NO_x$ it is required to use some models to have an approximate estimation.

$$E_{i,CO_2} = EI_{CO_2} m_{fuelburned} \qquad E_{i,NO_x} = EI_{NO_x} m_{fuelburned} \tag{5.9}$$

Because a comparison between two aircraft is being made, it is crucial to normalize Equation 5.8 with the SAR and the number of passengers. In this way, it can be obtained the kilograms of $CO_2$ per kilometer and seat, as Equation 5.10 shows.

$$CO_{2,equiv} = \frac{EI_{CO_2}}{SAR \cdot n} \cdot 1 + \frac{EI_{NO_x}}{SAR \cdot n} CF_{midpoint,NO_x} + \frac{L}{L \cdot n} CF_{midpoint,clouds} \tag{5.10}$$

In the Equation 5.10, $n$ refers to the number of passengers of the aircraft that is being analyzed. The term $L$ represents the distance to cover in the route, although its value does not matter because this terms disappear in this equation. The term $SAR$ is the Breguet parameter divided by the MTOW ($SAR = B/MTOW$), and the terms $EI$ represent the emission index of each specie. Finally, the term $CF$ represent the Characterization Factor. The $CF$ is the factor that relates the $NO_x$ and the contrails and cirrus with the $CO_2$. In order to known the kilograms of $CO_2$ per kilometer and seat is required to obtain the $CF$ for $NO_x$ and contrails and cirrus, and the EI for the $NO_x$ during the cruise. Once all this values are obtained, the kilograms of $CO_2$ per kilometer and seat can be calculated for each aircraft, and a comparison can be completed.

### 5.2.1 Characterization Factor

To obtain the $CF$ for $NO_x$ and contrails and cirrus, it is necessary to include the altitude dependency. This dependency is included in the procedure given by Schwartz (2011). To calculate the $CF$, the global temperature change after 100 years of maintained emissions is used to compare the climate influence of the aircraft. The Sustained Global Temperature Potential for the different species are calculated in Schwartz (2011) and gathered in Table 5.16. The way of calculating the $CF$ of each specie is multiplying every SGTP of the specie by the RF factor at the height of calculation, and diving it by the STGP of the $CO_2$. This is expressed in Equation 5.11.

$$CF_{midpoint,i} = \sum \frac{SGTP_{i,100} \cdot s_i(h)}{SGTP_{CO_2,100}} \tag{5.11}$$

**Table 5.16** Sustained Global Temperature Potential given (Schwartz 2011)

| Species | $SGTP_{i,100}$ |
|---|---|
| $CO_2$ (K/kg $CO_2$) | $3.58 \cdot 10^{-14}$ |
| Short $O_3$ (K/kg $NO_x$) | $7.79 \cdot 10^{-12}$ |
| Long $O_3$ (K/kg $NO_x$) | $-9.14 \cdot 10^{-13}$ |
| $CH_4$ (K/kg $NO_x$) | $-3.90 \cdot 10^{-12}$ |
| Contrails (K/km) | $1.37 \cdot 10^{-13}$ |
| Cirrus (K/km) | $4.12 \cdot 10^{-13}$ |

The $CF$ for the $NO_x$ emissions is then expressed in Equation 5.12.

$$CF_{midpoint,NO_x} = \frac{SGTP_{O_{3,S},100} \cdot s_{O_{3,S}}(h)}{SGTP_{CO_2,100}} + \frac{SGTP_{O_{3,L},100} \cdot s_{O_{3,L}}(h)}{SGTP_{CO_2,100}} + \frac{SGTP_{CH_4} \cdot s_{CH_4}(h)}{SGTP_{CO_2,100}} \tag{5.12}$$

For the induced cloudiness, the $CF$ is calculated with Equation 5.13.

$$CF_{midpoint,cloudiness} = \frac{SGTP_{contrails} \cdot s_{contrails}(h)}{SGTP_{CO_2,100}} + \frac{SGTP_{cirrus} \cdot s_{cirrus}(h)}{SGTP_{CO_2,100}} \tag{5.13}$$

The terms $s_i(h)$ represents the dependency of the RF with the height. This dependency is explained in Schwartz (2011). The Figure 5.4 is a graph with the variation of the values of the RF with the height. The value of $s(h)$ for the $O_{3,L}$ is the same than the value of the $CH_4$, and contrails and cirrus have also the same value. This means

$$s_{O_{3,L}}(h) = s_{CH_4}(h), \quad s_{contrails}(h) = s_{cirrus}(h) = s_{AIC}(h) \quad . \tag{5.14}$$

The cruise height is 35000 ft. Then the values for each specie can be obtained, and they are gathered in Table 5.17. The $CF$ value of the $NO_x$ and the contrails and cirrus is known, once all the values involved are known, as it shows Table 5.18.

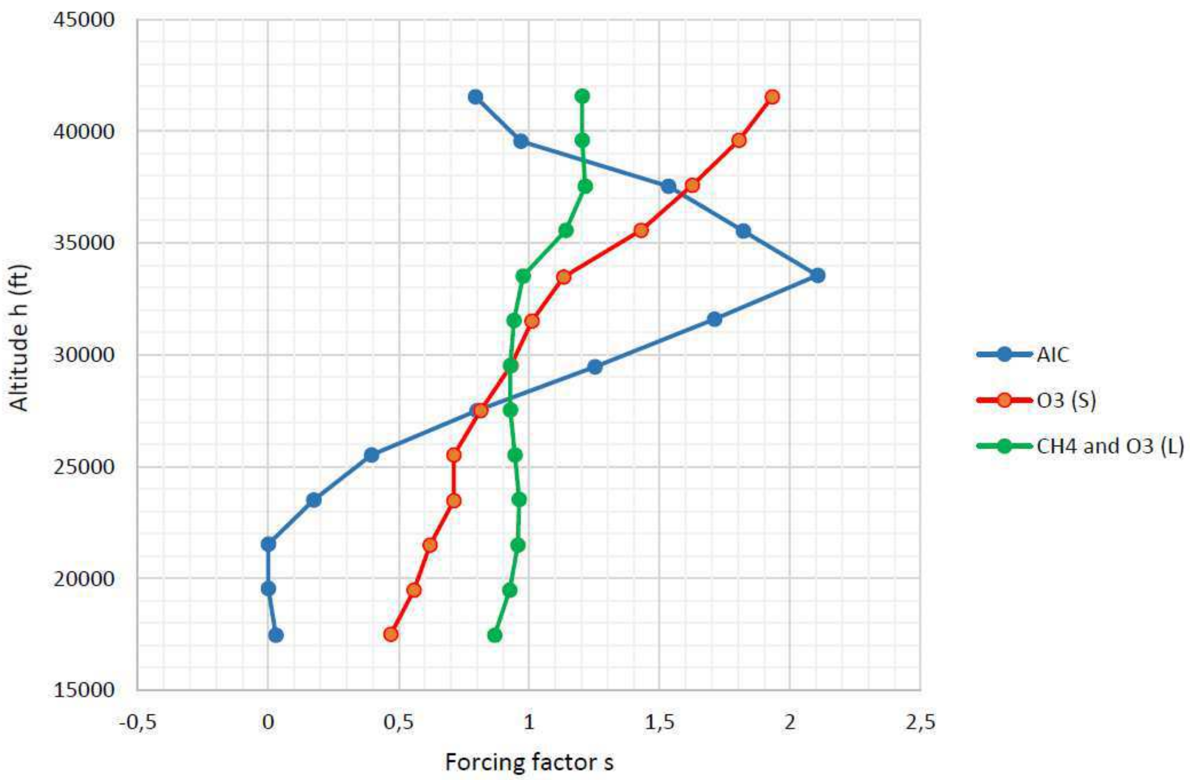


**Figure 5.4** RF factor dependency with the height by Schwartz (2011)

**Table 5.17** Forcing factors at the cruise height (Schwartz 2011)

| Species | Short $O_3$ | Long $O_3$ | $CH_4$ | Contrails | Cirrus |
|---|---|---|---|---|---|
| s(h) | 1.349 | 1.098 | 1.098 | 1.900 | 1.900 |

**Table 5.18** $CF$ of the $NO_x$ and the contrails and cirrus

| Species | $NO_x$ (kg $CO_2$/kg$NO_x$) | Contrails and cirrus (kg $CO_2$/km) |
|---|---|---|
| CF | 58.523 | 29.137 |

### 5.2.2 Emission Index of $NO_x$

It only remains to obtain the EI of the $NO_x$ during the cruise phase to know the equivalent $CO_2$ mass emitted. There are several methods to calculate the EI, but most of them use not available data to do the calculations. For this reason, and approximate method used by Boeing is also used in this master thesis (FAA 2005). The advantage of this method is that it only requires to know some features of the aircraft (MTOW, Breguet parameter, and altitude and velocity of the cruise) and some features of the engine, gathered in the Engine Emission Databank.

First of all, the uncorrected fuel flow is determined with the velocity of the cruise and the SAR parameter.

$$wf_{uncorr} = \frac{V_{CR}}{SAR} = \frac{V_{CR} MTOW}{B} \tag{5.15}$$

It is necessary to adjust this fuel flow to the altitude. This is done according to the formula

$$wf_{corr} = \frac{wf_{uncorr}}{\delta} \theta^{3.8} e^{0.2 M_{CR}^2} \quad , \tag{5.16}$$

with

$$\delta = \frac{p_{CR}}{p_0} = \frac{p_{CR}}{101325}, \qquad \theta = \frac{T_{CR}}{T_0} = \frac{T_{CR}}{288.15} \qquad . \tag{5.17}$$

For the *BAe 146-100*, the input values for the cruise are gathered in Table 5.19. Thus, the value of the corrected fuel flow can be calculated, being for this case $wf_{corrected} = 0.8255$ kg/s.

**Table 5.19** Input values for the *BAe 146-100*

| MTOW (kg) | Breguet parameter (km) | Temperature (K) | Pressure (Pa) | Mach |
|---|---|---|---|---|
| 38102 | 15741 | 218.65 | 23835 | 0.7 |

Once the corrected fuel flow is determined, it can be determined the uncorrected EI of the $NO_x$. This is done via a correlation between this two values. The correlation is made with the data of the Engine Emission Databank. The values of the fuel flow given in this databank have to be corrected with a correction factor which depends on the operation mode, as Table 5.20 shows. The adapted fuel flow is then calculated as Equation 5.18 expresses.

$$wf_{adap} = wf_{unadap} \cdot r \quad . \tag{5.18}$$

Each value of the adapted fuel flow has attached a value of an uncorrected $EI_{NO_x}$, thanks to the information of the Engine Emission Databank (Table 5.21). Thus, the adapted fuel flow

**Table 5.20** Correction factors (FAA 2005)

| Species | Taxi in | Take off | Climb out | Approach | Taxi out |
|---|---|---|---|---|---|
| Correction factor | 1.100 | 1.010 | 1.013 | 1.020 | 1.100 |

**Table 5.21** $EI_{NO_x}$ for the different flight phases (EASA 2017)

| Species | Taxi in | Take off | Climb out | Approach | Taxi out |
|---|---|---|---|---|---|
| EI $NO_x$ (g/kg fuel) | 3.78 | 13.35 | 10.56 | 6.6 | 3.78 |
| Adapted fuel flow (kg/s) | 0.0449 | 0.3617 | 0.2993 | 0.1055 | 0.0449 |

is plotted with its corresponding value of $EI_{NO_x}$ in a logarithmic scale (Figure 5.5). With the fuel flow value obtained in Equation 5.16, and using the regression obtained in Figure 5.5, the uncorrected $EI_{NO_x}$ for the cruise is $EI_{NO_x,uncorr} = 20.33$ g/kg fuel.

The uncorrected EI of $NO_x$ has to be corrected with the atmospheric effects. For this reason the corrected EI of $NO_x$ is determined with Equation 5.19.

$$EI_{NO_x,corr} = EI_{NO_x,uncorr} \left( \frac{\delta^{1.02}}{\theta^{3.3}} \right)^{0.5} e^{H} \tag{5.19}$$

Where $H$ represents the humidity factor. This value is determined with the Equation 5.20.

$$H = -19 \left( \frac{0.37318 p_v}{p_{CR} - 0.6 p_v} - 0.0063 \right) \quad , \tag{5.20}$$

with

$$p_v = 100.00508 \cdot 10^{\beta} \tag{5.21}$$

and

$$\begin{aligned} \beta = {} & 7.90298 \left( 1 - \frac{373.16}{0.01 + T_{CR}} \right) + 3.00571 + 5.02808 log_{10} \left( \frac{373.16}{0.01 + T_{CR}} \right) + \\ & + 1.381610 \cdot 10^{-7} \left[ 1 - 10^{11.344 \left( 1 - \frac{373.16}{0.01 + T_{CR}} \right)} \right] + \\ & + 8.1328 \cdot 10^{-3} \left[ 10^{3.49149 \left( 1 - \frac{373.16}{0.01 + T_{CR}} - 1 \right)} \right] \quad . \end{aligned} \tag{5.22}$$

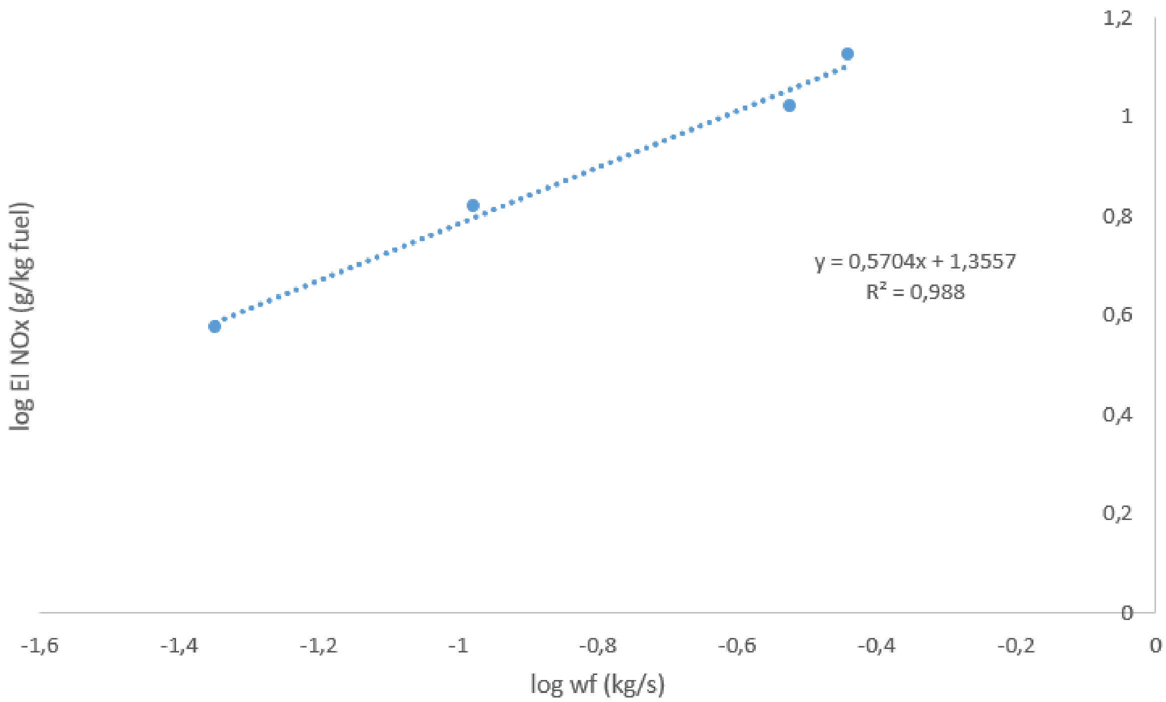


**Figure 5.5** Correlation between EI $NO_x$ and adapted fuel flow

Substituting all the values in their respective equations, the $EI_{NO_x,corr}$ for the *BAe 146-100* in the cruise phase is $EI_{NO_x,corr} = 17.27$ g/kg fuel.

### 5.2.3 Equivalent $CO_2$ Mass Emitted

With all the values of the Equation 5.10 determined, it is possible to obtain the equivalent mass of $CO_2$ emitted per kilometer and seat class of the *BAe 146-100*. To calculate the emitted mass of $CO_2$ per kilometer and seat class, it is required then to use Equation 5.23. This equation is the same that Equation 5.10 but introducing the relative surface that each class occupy and the number of seats of the class. Thus, the equivalent $CO_2$ mass per seat class and specie can be determined for the *BAe 146-100*. The results are listed in Table 5.22.

$$CO_{2,equiv} = \frac{S_{class}}{S_{total}} \left[ \frac{EI_{CO_2}}{SAR \cdot n_{class}} + \frac{EI_{NO_x}}{SAR \cdot n_{class}} CF_{midpoint,NO_x} + \frac{1}{n_{class}} CF_{midpoint,clouds} \right] \tag{5.23}$$

**Table 5.22** Equivalent $CO_2$ mass emitted per km and seat class for each specie for the *BAe 146-100*

| | First class | | | Economic class | | |
|---|---|---|---|---|---|---|
| Species | $CO_2$ | $NO_x$ | Clouds | $CO_2$ | $NO_x$ | Clouds |
| Equivalent $CO_2$ (g/km seat) | 121.9 | 39.0 | 13.5 | 88.4 | 28.3 | 9.8 |

The $EI_{CO_2}$ is fixed and non dependant on the type of engine, and the $CF$ for the clouds is also constant. Then, it can be calculated the emitted mass of $CO_2$ per kilometer and seat class for the *E-FAN X* due to the $CO_2$ and the contrails and cirrus, introducing in Equation 5.23 the *SAR* of the *E-FAN X*, and its number of seats and relative surface. Also the percentage difference between both aircraft can be determined. This can be seen in Table 5.23.

**Table 5.23** Equivalent $CO_2$ mass emitted per km and seat class for each specie for the *E-FAN X*

| | First class | | Economic class | |
|---|---|---|---|---|
| Species | $CO_2$ | Clouds | $CO_2$ | Clouds |
| Equivalent $CO_2$ (g/km seat) | 141.5 | 15.8 | 102.6 | 11.5 |
| Percentage difference (%) | 16.08 | 17.04 | 16.06 | 17.35 |

The new performance of the aircraft with the new number of passengers generates an increase of about 16% to 17% in the emissions per seat. The value due to the $CO_2$ only can be enhanced with a better *SAR*. If the *SAR* of the *E-FAN X* increases, then the emission per seat decreases. But for the contrails and cirrus, this value can not be enhanced. Only an increase in the number of passengers would enhanced the emissions due to the contrails and cirrus. It is unlikely that the new aircraft will have a better performance in this area.

Regarding the value related to the $NO_x$, it is not possible to obtain the mass of $CO_2$ per kilometer seat for the *E-FAN X*, because it is not known the $EI_{NO_x}$ of the *AE 2100A*. But it can be determined the $EI_{NO_x}$ that nthe *E-FAN X* must have, setting as limit value of emission per seat the same value that the *BAe 146-100* has. The new aircraft must have at least the same value of emissions per kilometer and seat if it wants to be as eco-friendly as the old aircraft. Using the *SAR* of the new aircraft, its number of seats for the two different classes, and working only with the $NO_x$ term of the Equation 5.23, it can be determined the $EI_{NO_x}$ for each seat class (Equation 5.24). With the relative surface each class occupy, the $EI_{NO_x}$ of the *AE 2100A* can be calculated (Equation 5.25). The results are listed in Table 5.23.

$$EI_{NO_x,class} = 1.16 \frac{S_{total}}{S_{class}} \frac{CO_{2,equiv,class} SAR_N n_{class}}{CF_{midpoint,NO_x}} \tag{5.24}$$

$$EI_{NO_x,N} = \frac{S_{first}}{S_{total}} EI_{NO_{x,first}} + \frac{S_{economic}}{S_{total}} EI_{NO_{x,economic}} \tag{5.25}$$

**Table 5.24** $EI_{NO_x}$ for the *E-FAN X*

| | First class | Economic class |
|---|---|---|
| Equivalent $CO_2$ (g/km seat) | 39.0 | 28.3 |
| $EI_{NO_x,class}$ (g $NO_x$/kg fuel) | 14.86 | 14.86 |
| $EI_{NO_x}$ (g $NO_x$/kg fuel) | 14.86 | 14.86 |

In order to have the same emitted mass of $CO_2$ per kilometer and seat due to the $NO_x$, the total $EI_{NO_x}$ must be 14.86 g/kg fuel. And again, this reduction has to be achieved only with the performance of one engine, which means the new engine must have

$$14.86 = \frac{3}{4}17.27 + \frac{1}{4}EI_{NO_x,N}, \quad EI_{NO_x,N} = 7.63 \text{ g/kg fuel} \quad . \tag{5.26}$$

This supposes a reduction in the $EI_{NO,x}$ for the new engine of $(7.63 - 17.27)/17.27\ \% = -55.82\ \%$.

After showing all the results, it has been demonstrated that the *E-FAN X* will also probably have a worse environmental performance in the cruise flight phase. This results, together with environmental results of the Local Air Quality section, show that the *E-FAN X* is going to be less eco-friendly than the *BAe 146-100*, or at least that it is improbable to be more eco-friendly. The reduction in the number of passengers together with the new performance of the aircraft makes this new aircraft more polluting, due to the ratios per passenger increases. Table 5.25 summarizes the performance the *AE 2100A* must have in the different areas in order to make the *E-FAN X* have the same emissions per seat than the *BAe 146-100*.

**Table 5.25** Reduction in emissions required for the *AE 2100A*

| | $NO_x$ emission | Ozone emission | PM emissions | $EI_{NO_x}$ |
|---|---|---|---|---|
| Percentage difference (%) | -57.39 | -57.41 | -57.36 | -55.82 |

## 5.3 Noise Pollution

The movement of the aircraft through the air generates noise. There are three main sources of noise in an aircraft: mechanical noise, aerodynamic noise and noise from aircraft systems. During all the flight phases, the noise is going to affect the passengers. The cruise phase will establish the comfort of the passengers, due to it is the longest flight phase. But during the take off and approach, the noise is going to affect the people who live in the surroundings of the airport. The passengers will suffer the noise only during the trip, but the people living in the surroundings are going to be affected whenever the airport is working. It has been demonstrated in many scientific reports that the exposure to noise constitutes a health risk (Franssen 2004). While the noise during cruise is a matter of comfort, the noise in the surroundings of the airports is a public concern and a health concern. Governments have enacted extensive controls that apply to aircraft designers, manufacturers, and operators, resulting in improved procedures and cuts in pollution. The aeronautic world is moving more and more into a less noisy aircraft.

The evaluation of the noise is difficult, for different reasons. One reason is that the physic of the noise itself is complicated and involve so many factors. In the transmission of the noise through the air, when it reaches a solid surface, the reflection and transmissions phenomena occurs. This modify the form of the original noise, and make the problem more complicated. Another reason is the features of the problem object to study. In an aircraft, the aerodynamic noise arises from the airflow around the aircraft fuselage and control surfaces. So every part of the fuselage is generating, reflecting and transmitting noise. The problem gets really tough to study. And another factor that make the noise study hard is the difficulty of determining exactly the amount of noise one system is going to generate. The engines, for example, have some mobile parts, in charge of the generation of the noise. Depending on so many features of this mobile parts (size, thickness, type of material, type of union among all the pieces, performance...) the amount of noise generated is different. But also the relation of all this mobile parts with the rest of the engine is involved in the total amount of noise. Giving a generic expression that gives the noise generated by one engine depending on simple parameters of the engine itself is not easy, but also not accurate. For these reasons, the study done in this master thesis is just a simply approach to the problem, in order to give a first results of how the transformation of the aircraft is going to affect the noise emission.

Nevertheless, the study of the noise have some advantages. Due to the characteristics of the sound, when there are two sources of noise, the total amount of noise generated by this two sources is not the sum of the noise of each source. The sensitivity of the human hearing to the variations of acoustic intensity follows a logarithmic scale. Following the acoustic laws (Lamancusa 2009; SINTEC 2016), the noise felt by one hearer due to one source of noise is

$$I = 10log_{10}\frac{I_p}{I_0} \quad \text{dB} \quad . \tag{5.27}$$

The term $I_p$ represents the sound intensity of the noise in the place where the hearer is emplaced, and $I_0$ is the threshold value corresponding to the threshold of human hearing. Normally it is not known the power of the sound where the hearer is placed, it is known the power of the sound in its source of emissions ($I_x$). Considering an spherical propagation of the noise (Lamancusa 2009; SINTEC 2016), the sound intensity in one point separated a distance $r$ of the origin is

$$I_P \text{ (dB)} = I_X \text{ (dB)} - 20log_{10}r \text{ (m)} - 11 \text{ (dB)} \quad . \tag{5.28}$$

When there is $n$ sources of noise, with their corresponding value of power, the way of obtaining the total amount of noise perceived in a point $P$ is with Equation 5.29 (Lamancusa 2009; SINTEC 2016).

$$I_T = 10log_{10}\left(\sum_{i=1}^{n} 10^{I_P(i)/10}\right) \quad \text{dB} \tag{5.29}$$

The characteristics of the noise makes then that the sources with more power absorb the sources with less power. This means that if there is one source with high value of power emitted, and another source with a low value, the final result of power will be the same as having only the source of noise with high power. The noise of the small source is not going to be perceived, only the sound of the high source. This characteristic of the physic of the sound is going to be used for the noise evaluation.

The *BAe 146-100* has four turbojets emplaced in the wing. With the transformation into an *E-FAN X*, one of this turbojets will be replaced with one electric engine, which makes less noise. But one turboshaft will be emplaced in the rear fuselage, generating noise inside the fuselage.

One hearer outside the aircraft will only perceived the noise generated by the engines and the fuselage. The noise of the turboshaft will be attenuated by the fuselage, and then not heard due to its lower value of power perceived. Depending on how is managed the noise generated by this turboshaft, the passengers will perceive the noise generated by fuselage and engines or they will perceive the noise generated by fuselage, engines and turboshaft.

In order to do a first simply approach to the noise evaluation, the noise generated by the fuselage and engines is going to be study. A spherical evolution of the noise generated by the engines is assumed. The presence of the wings and all its effects are not taken into account. Looking at the dimensions of the *BAe 146-100*, a first estimation of the distance of the engines to the center of the fuselage could be 4 meters for the inner engines, and 7.5 meters for the outer engines. The noise generated by the engines is not known in the old configuration either in the new configuration. But it is known that for the *BAe 146-100* all the four engines generates the same amount noise. The sound intensity of the inner engines would be

$$I_1 = I_{eng} - 20log_{10}4\ \text{m} - 11\ \text{dB} \quad , \tag{5.30}$$

and for the outer engines

$$I_2 = I_{eng} - 20log_{10}7.5\ \text{m} - 11\ \text{dB} \quad . \tag{5.31}$$

The noise produced by the fuselage during the cruise phase can be estimated with Equation 5.32 (Lasagna 1976).

$$I_{AF}\ (\text{dB}) = 10log_{10}V_{CR}^5\ (\text{m/s}) + 10log_{10}W_{CR}\ (\text{N}) - 74\ (\text{dB}) \tag{5.32}$$

Introducing the value of the cruise velocity, and taking as weight for the cruise the $MTOW$, the result for the fuselage is $I_{AF} = 97.57$ dB. Assuming this fuselage noise is placed in the center of the fuselage, the total sound intensity in the center of the fuselage for the *BAe 146-100* would be, using Equation 5.29,

$$I_O = 10log_{10}\left(2\cdot 10^{I_1/10} + 2\cdot 10^{I_2/10} + 10^{97.57/10}\right) \quad \text{dB} \quad . \tag{5.33}$$

For the *E-FAN X*, the reduction in noise of the electrical engine modifies the total amount of noise emitted. The engine replaced is one of the two engines close to the airframe, so the distance is 4 meters. The sound intensity of this engine perceived in the center of the fuselage would be

$$I_3 = \alpha I_{eng} - 20log_{10}4\ \text{m} - 11\ \text{dB} \quad . \tag{5.34}$$

Where $\alpha$ represents the unknown reduction in noise of the electric engine with respect to the old engine. Thus, the sound intensity of the *E-FAN X* is

$$I_N = 10log_{10}\left(10^{I_1/10} + 2\cdot 10^{I_2/10} + 10^{I_3/10} + 10^{97.57/10}\right) \quad \text{dB} \quad . \tag{5.35}$$

It is not possible to know the noise generated by the two aircraft, but an estimation of the noise reduction for the new aircraft can still be realized. First of all is necessary to divide both values of sound intensity for each aircraft.

$$\mathrm{I} = \frac{I_N}{I_O} = \frac{10log_{10}\left(10^{I_1/10} + 2\cdot 10^{I_2/10} + 10^{I_3/10} + 10^{97.57/10}\right)}{10log_{10}\left(2\cdot 10^{I_1/10} + 2\cdot 10^{I_2/10} + 10^{97.57/10}\right)} \quad . \tag{5.36}$$

The value of I is a function of the noise produced by the non electrical engines ($I_{eng}$) and the reduction in noise of the electrical engine ($\alpha$). Taking $I_{eng}$ as variable, and setting a fixed value for $\alpha$, the function I($I_{eng}$) can be plotted (Figure 5.6). Changing the value of $\alpha$ within a reasonable range of values, the maximum reduction in noise can be known in each case, and also the value of $I_{eng}$ that generates this highest reduction. Table 5.26 list the minimum value of I for each $\alpha$, and the value of $I_{eng}$ where the maximum reduction is achieved.

**Table 5.26** Minimum value of I

| | | | | | | |
|---|---|---|---|---|---|---|
| $\mathrm{I}_{min}$ | 0.9818 | 0.9818 | 0.9818 | 0.9820 | 0.9828 | 0.9865 |
| $\alpha$ | 0.70 | 0.75 | 0.80 | 0.85 | 0.90 | 0.95 |
| $I_{eng}$ | 131.75 | 131.75 | 131.79 | 131.97 | 132.50 | 134.07 |

With this first simply approach, several conclusions can be made. The first conclusions is that the maximum achievable reduction in noise emission is asymptotic with the reduction in noise reached in the electric engine. This means that a zero noise emission electrical engine can be emplaced in the aircraft, but the reduction in noise would not be higher than $\sim 1.82\%$. Another conclusion is that this highest reduction is only going to be achieved if the engines have a noise emission of 132 dB. A lower value would mean no reduction in the noise emitted (the fuselage would be the main source of noise emission), and a higher value, a reduction less than $1\%$. For a conventional aircraft, the noise generated by the engines during cruise is in the range from 110 dB to 130 dB. Using this values, and with this simply approach, it is confirmed that the possible reduction of noise in the new configuration would be between $0.5\%$ and $1.5\%$.

It has to be noticed that this results are highly influenced by the noise generated by the fuselage calculated in Equation 5.32. A lower value of the sound intensity by the fuselage will displace the curve to the left, into a lower values of $I_{eng}$. The opposite would happen if the value for the fuselage is higher. Nevertheless, as mentioned before, the value of the reduction shall be selected in the range from 110 dB to 130 dB, the average noise of the conventional aircraft. Also all this results has been obtained with the noise produced by the fuselage during the cruise. Only the passengers will perceive this noise, reduced by the corresponding devices of noise reduction. The reduction in noise achieved by the sound dumping devices has not been taken into account,

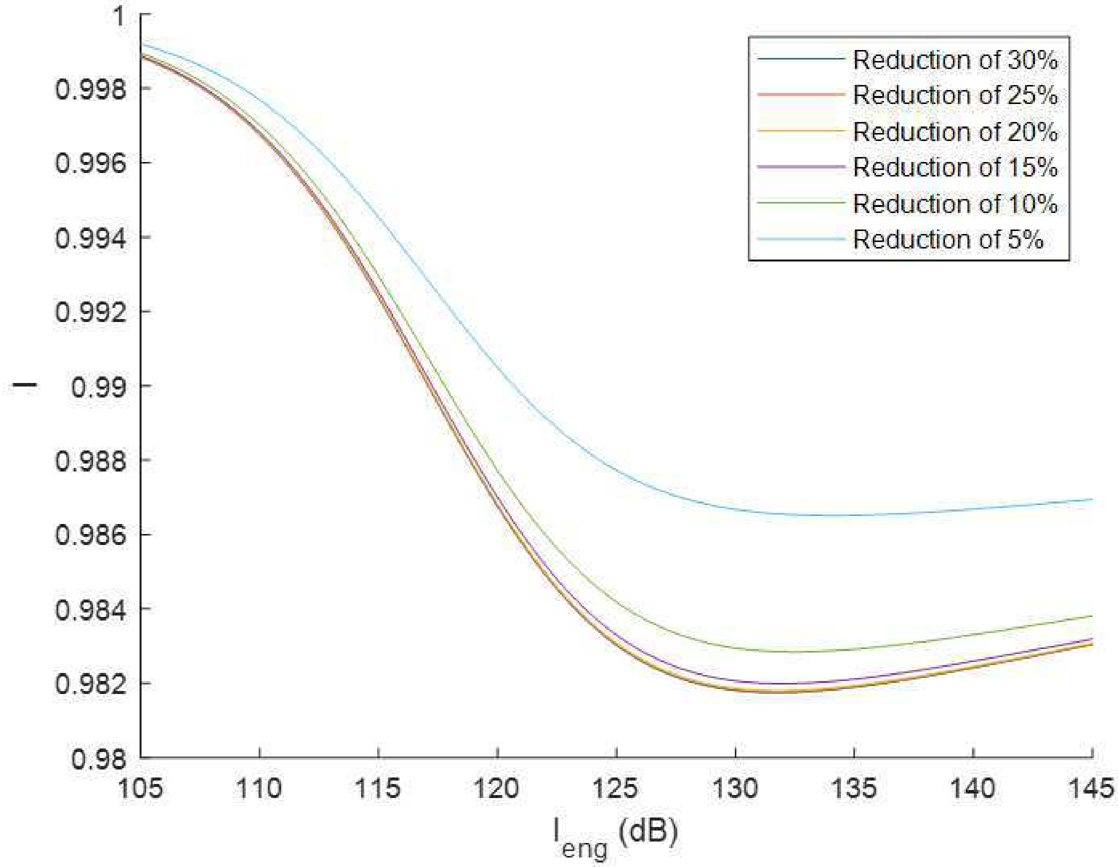


**Figure 5.6** Plot of the function I with different values of $\alpha$

because they will affect the same to all the sources of sound. The reduction achieved is the same for the engines and fuselage. But here, inside the fuselage, the noise produced by the turboshaft plays a role. If the noise of the turboshaft wants to be not perceived by the passengers, its value shall be lower than the noise perceived in the cabin due to the engines and fuselage after the reduction.

Another simply first study regarding the noise during the take off and approach can be done. For this two flight phases, the distribution of Effective Perceived Noise of a conventional aircraft is as Figure 5.7 shows. The EPNdB is a measure of the relative noisiness of an individual aircraft pass by event. It is used for aircraft noise certification and applies to an individual aircraft. Separate ratings are stated for takeoff, overflight and landing events, and represent the integrated power sum of noisiness during the event. Instantaneous value of noisiness is not computed with the EPNdB. However, this values can be used to do a first approach to the noise problem during take off and approach phases. Looking at Figure 5.7, the approach phase result to be more critical than the take off in the noise emission area.

Now it can be made the assumption that all the sources of noise are concentrated in one determined point, because one hearer is going to be placed far away from the aircraft. The distance from this hearer to the engines and the fuselage is then the same. The total amount of noise

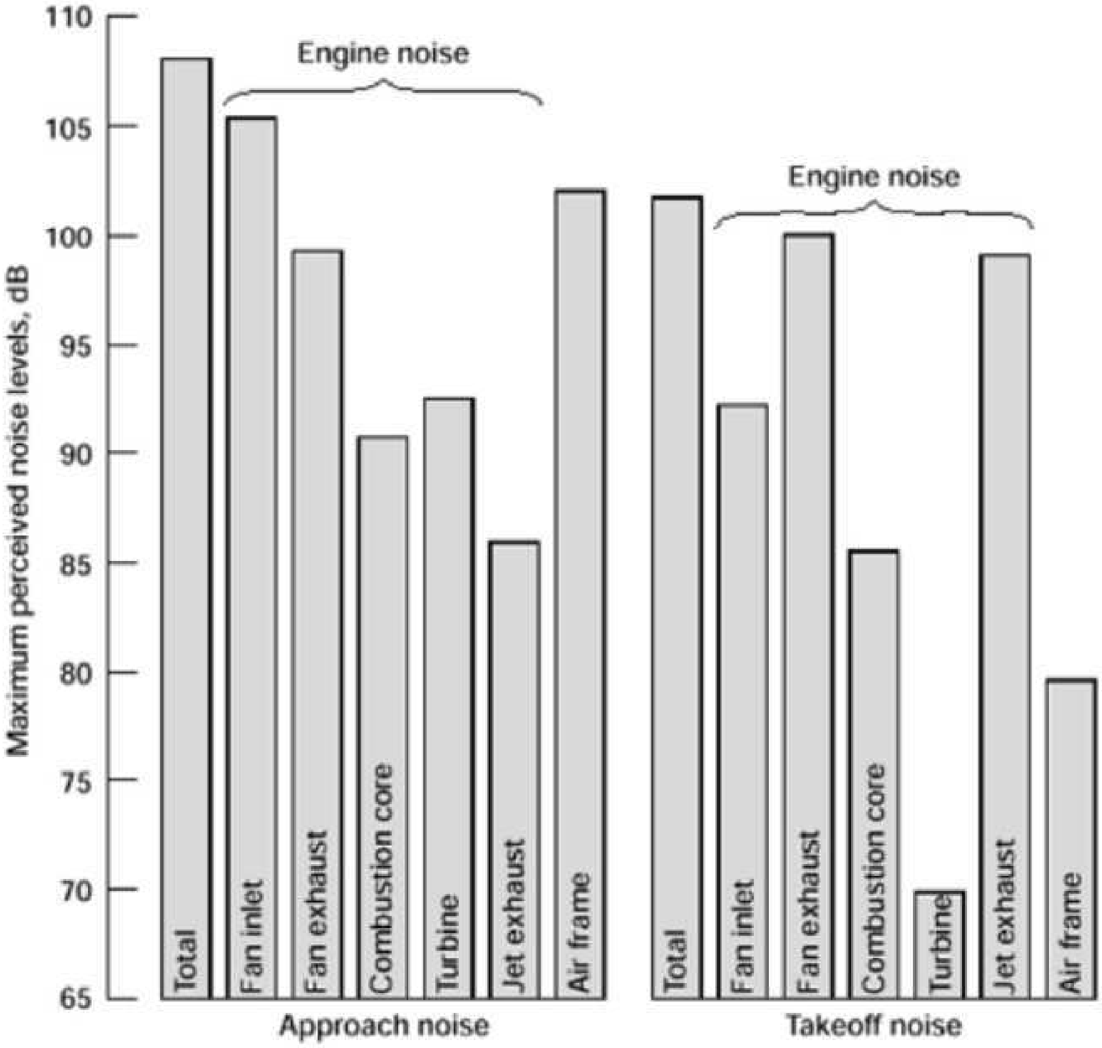


**Figure 5.7** Noise distribution during approach and take off (Lasagna 1976)

produced by the four engines and fuselage of *BAe 146-100* would be, using Equation 5.29,

$$I_O = 10log_{10}\left(4 \cdot 10^{I_{eng}/10} + 10^{102/10}\right) \quad \text{dB} \quad . \tag{5.37}$$

It has been taken for the fuselage a value of 102 dB, following the estimation of Figure 5.7. Again, the term $I_{eng}$ represents the unknown value of noise produced by the engines. For the *E-FAN X*, both aircraft have the same fuselage, so the total amount of noise produced is

$$I_N = 10log_{10}\left(3 \cdot 10^{I_{eng}/10} + 10^{\alpha I_{eng}/10} + 10^{102/10}\right) \quad \text{dB} \quad . \tag{5.38}$$

Again, $\alpha$ represents the reduction in noise achieved by the electrical engine. Dividing both values of sound intensity, now the function I is

$$\mathrm{I} = \frac{I_N}{I_O} = \frac{10log_{10}\left(3\cdot 10^{I_{eng}/10} + 10^{\alpha I_{eng}/10} + 10^{102/10}\right)}{10log_{10}\left(4\cdot 10^{I_{eng}/10} + 10^{102/10}\right)} \quad . \tag{5.39}$$

The function I($I_{eng}$) can be plotted again with a different values of $\alpha$ (Figure 5.8). Table 5.27 gathers the minimum values of I for the different $\alpha$ and the value of $I_{eng}$ where this minimum occurs. The maximum reduction occurs when the value of $I_{eng}$ is near 110 dB. The maximum reduction in noise achieved is again asymptotic with the reduction in noise reached by the electrical engine. The maximum reduction is $\sim 1.03\%$. Taking a look at Figure 5.7, the value of EPNdB for the engine during the approach is near 105 dB. For this value, the reduction of noise is $\sim 1\%$ with an engine 25% less noisy. For the expected EPNdB of normal engines, in the range from 100 dB to 130 dB, the reduction is between 0.8% and 1.03%. The maximum reduction in noise that is possible to achieve with the new less noisy engine is almost negligible.

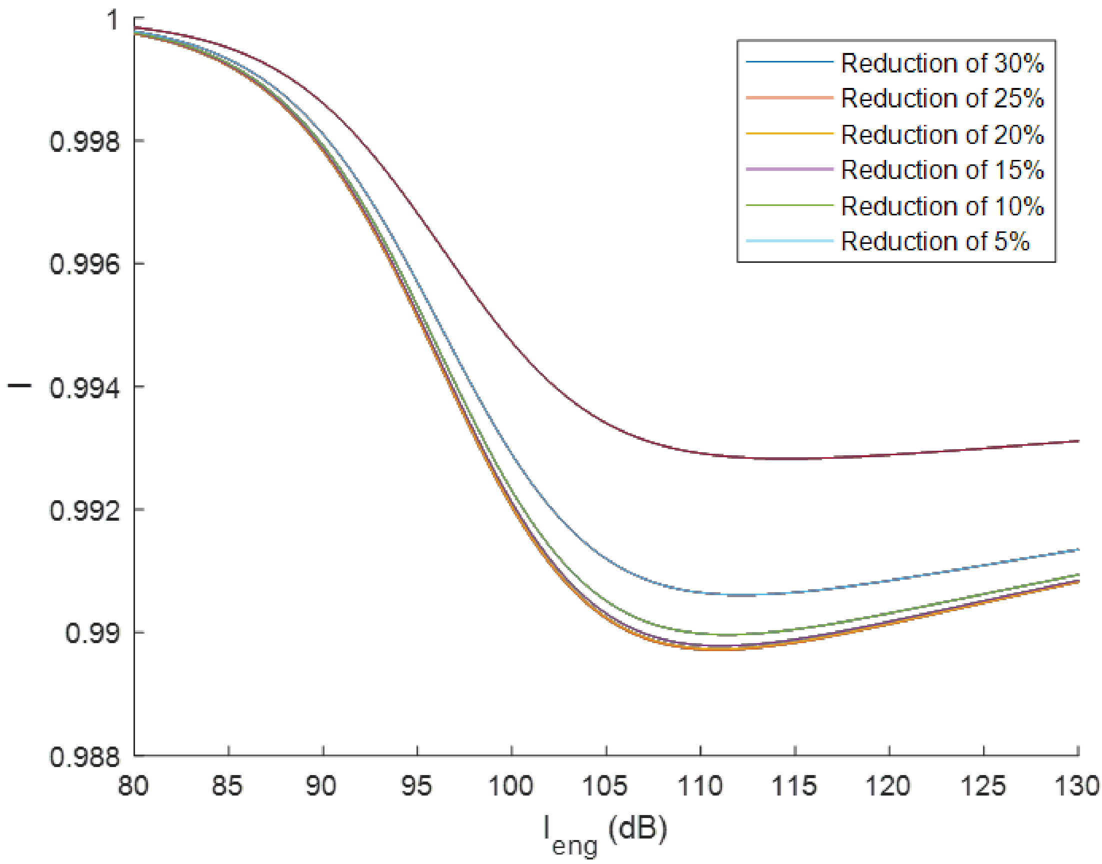


**Figure 5.8** Plot of the function I with different values of $\alpha$

With this two simply approaches to the noise evaluation, one conclusion can be made: it is meaningless trying to manufacture an engine with low noise emission if the rest of sources are still producing high levels of noise. If a reduction in noise emission wants to be achieved, then the whole aircraft shall be redesign to be less noisy. Reducing the sound level of one of the

**Table 5.27** Minimum value of I

| $I_{min}$ | 0.9897 | 0.9897 | 0.9898 | 0.9900 | 0.9906 | 0.9930 |
|---|---|---|---|---|---|---|
| $\alpha$ | 0.70 | 0.75 | 0.80 | 0.85 | 0.90 | 0.95 |
| $I_{eng}$ | 110.85 | 110.85 | 111.11 | 111.36 | 112.11 | 114.62 |

sources, maintaining the rest of sources with the same high level noise will almost not change the total value of noise emitted. Replacing one turbojet by one electric engine, will not mean a huge reduction in the noise emission. Moreover, with the presence of the turboshaft inside the fuselage, another problem arises. It is required to mitigate this new source of noise emplaced inside the fuselage. With all this ideas, it is then expected that the *E-FAN X* is going to be just slightly less noisy than the *BAe 146-100*.

It has to be mentioned that no attenuation devices have been taking into account in the study. The external sources of noise that the passenger perceive are the noise emissions due to the engines and airframe. This sound is attenuated by the fuselage. With the replacement of maybe the four engines, if the noise emission of this engines are low, only the fuselage would be heard. With the fuselage as only source of noise, and with an effective attenuation system, maybe the total noise perceived by the passenger inside the aircraft is less than the conventional situation. But still it has to be evaluated together with the noise produced inside the fuselage due to the turboshaft.

# 6 Summary and Conclusions

The objective of this master thesis was to evaluate one specific electrical aircraft project. With the growth rate of the aviation sector, thus the emissions emitted, greener ways of propulsion are required, to achieve a sustainable development. But the reality is that this sort of propulsion for the aircraft is still not ready to join the sector. And the main reason is due to the energetic difference that the electrical and chemical propulsion have got. As mentioned in Chapter 2, an average battery storage 60 times less energy than the kerosene. It is true that the battery is able to transform more percentage of energy in movement than the kerosene, but the huge difference in the energy stored makes the difference. Thus, flying with kerosene allows the aircraft to fly with more space for the passengers than flying with batteries. More passengers to share the emissions with, and also all the costs.

This energetic difference between the batteries and the kerosene were one of the main facts that drove the evaluation of the *E-FAN X*. The original project is expected to have a 2 tons battery with 2 MW. But during the development of the master thesis, the conclusion that this battery is not required was reached, as it is explained in Chapter 3. There are two main reasons to support this affirmation. The first reason is that this battery was required to support the electrical engine during take off and climb. But the performance of the engine itself is enough to cover this flight phases. So the presence of the battery is not compulsory, it is only maybe necessary to improve the performance in this areas, saving fuel. But here the second reason arises. With the current technology, and with the features of this project, the save in fuel consumed is not enough to cover the increase in weight that the battery supposes. This means that the increase in weight due to the presence of the battery must be compensated only with the decrease in the payload weight. And this generates as result an increase in all the ratios per passenger in every calculation, factor that plays against the *E-FAN X*. The fact of removing the batteries is a huge change with respect to the real project. With the battery on board, the reduction of passenger would be even more numerous, and the results would be even worse for the new aircraft.

Moving to the results, even without the additional mass due to the presence of the battery, the necessary reduction in the number of passengers makes the *E-FAN X* inferior in every scenario. In Chapter 4, the DOC model together with the fuel consumption model used, generates a DOC per seat mile between 10% and 11% more expensive for the hybrid aircraft. In the route with the less DOC per seat mile, the *E-FAN X* has a performance 12% more expensive than the *BAe 146-100*. This makes the new aircraft completely incompetent with respect to the old aircraft in the economic area. From to the environmental results in Chapter 5, it has been demonstrated that the features the new engine must have in order to make the *E-FAN X* as eco-friendly as the *BAe-146-100* are so demanding. The new engine shall have a reduction of about 57% in the emissions of $NO_x$, Ozone and PM to mitigate the reduction in the number of passengers. Also the $EI_{NO_x}$ of this new engine shall be approximately 55% less than the old engine. Regarding the equivalent $CO_2$ mass emitted, the new configuration is expected to have an increase between 16% and 17% with respect the old configuration. It is foreseeable then that the new aircraft is going to be more pollutant. In addition, the new aircraft is going to be slightly less noisy than the old aircraft. The performance of the new engine is expected to reduce the noise about $\sim 1\%$. Moreover, there is an additional source of noise in the aircraft: the turboshaft in the rear fuselage. Depending on how the noise of this turboshaft is managed, the passengers will perceive more, less or equal noise. These three evaluations confirm one fact: with the current technology, the *E-FAN X* is expected to be less competitive than the *BAe 1466-100* in every area. The new aircraft is going to be more expensive to operate, more pollutant, and probably slightly less noisy.

Nevertheless, this results shall not bring desperation and depression for the future of the aviation. It is true that the results are not encouraging, but it has to be mentioned that this project is one of the first in its kind. After the analysis of the *E-FAN X* project, and comparing this project with another electrical projects, it could be said that maybe this project has not being raised correctly. Building an aircraft from zero could optimize some parameters that were fixed for this project, parameters as the glide ratio, the MTOW, the $S_W$, $M_{CR}$... Another way of designing could generate better results. Solving a problem from zero instead of transforming one existing solution always improve the results.

The fact of flying is so demanding energetically talking. It requires more energy than the other ways of transport. With the current technology regarding the batteries and electrical propulsion, it is not possible to fly in a competitive position with respect to the conventional aircraft. Then, right now, the hybrid-electrical aviation is possible, but neither profitable nor greener.

It is usual to see in the news how all this electrical projects are sold as the future of aviation. It is being claimed that the electrical aviation will save the World, making this conveyance completely eco-friendly. But good results still do not arrive in the market, and meanwhile the conventional aviation keeps growing. It is required more dedication in this projects, in order to finally decide whether this sort of aviation is going to be a real option or not. Until that moment, the conventional aviation will be still working. And all the environmental problems related to this kind of aviation will stay.

# References

AERO 2011. *Aircraft Preliminary Sizing Tool (PreSTo).* Hamburg, Germany: HAW Hamburg. Available at: https://www.fzt.haw-hamburg.de/pers/Scholz/PreSTo.html

AERO 2013. *Optimization in Preliminary Aircraft Design.* Hamburg, Germany: HAW Hamburg. Available at: https://www.fzt.haw-hamburg.de/pers/Scholz/OPerA.html

AIRBUS, 2018. *Global Market forecast 2018-2037*. Blagnac, France: Airbus. Available at: https://www.airbus.com/aircraft/market/global-market-forecast.html archived as: https://perma.cc/BNU6-B3BV

AIRBUS, 2019. *CityAirbus*. Blagnac, France: Airbus. Available at: https://www.airbus.com/innovation/urban-air-mobility/vehicle-demonstrators/cityairbus.html, archived as: https://perma.cc/8NYW-SG8F

BJORN, Fehrm, 2017. *Airbus, Rolls-Royce and Siemens develops Hybrid-Electric demonstrator.* Bainbridge Island, Seattle, WA: Leeham, News and Analysis. Available at: https://leehamnews.com/2017/11/29/airbus-rolls-royce-siemens-develops-hybrid-electric-demonstrator, archived as: https://perma.cc/D3ZJ-PTQM

BOEING, 2018. *Commercial Market Outlook 2018-2037.* Seattle, WA: Boeing Commercial Airplanes. Available at: https://www.boeing.com/resources/boeingdotcom/commercial/market/commercial-market-outlook/assets/downloads/2018-cmo-09-11.pdf ,archived as: https://perma.cc/8NXK-NLWX

BOWMAN, Cheryl, 2016. *Visions of the Future: Hybrid Electric Aircraft Propulsion.* National Aeronautics and Space Administration (NASA). Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170002633.pdf, archived as: https://perma.cc/2L2P-WJYL

EASA, 2017. *ICAO Aircraft Engine Emissions Databank, 2017.* Bruxelles, Belgium: EASA. Available at: https://www.easa.europa.eu/document-library/icao-aircraft-engine-emissions-databank, archived as: https://perma.cc/9EE6-2KA8

EASA, 2019. *Special Condition for small-category VTOL aircraft.* Bruxelles, Belgium: EASA. Available at : https://www.easa.europa.eu/sites/default/files/dfu/SC-VTOL-01%20with%20highlights.pdf, archived as: https://perma.cc/WU6A-6QGW

EU, 2011. *Flightpath 2050 Europe's Vision for Aviation*. European Union: European Comission. Available at:

https://ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf, archived as: https://perma.cc/P89T-SD7M

FAA, 2005. *System for assessing Aviation's Global Emissions Version 1.5 Technical Manual.* SW Washington: United States Department of Transportation. Available at: https://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/sage/media/FAA-EE-2005-01_SAGE-Technical-Manual.pdf archived as: https://perma.cc/5UU3-JMZG

FLIGHT, 2001. *World Airliners.* Flight International. Available at: https://www.flightglobal.com/pdfarchive/view/2001/2001%20-%202962.html archived as: https://perma.cc/AZR7-E3ZY

FRANSSEN, E. A. M., van Wiechen, C. M. A. G., Nagelkerke, N. J. D., Lebret. E. 2004. *Aircraft noise around a large international airport and its impact on general health and medication use*. National Institute for Public Health and the Environment (RIVM), Centre for Environmental Health Research, Bilthoven, Netherlands. Available at: https://oem.bmj.com/content/oemed/61/5/405.full.pdf archived as: https://perma.cc/88U5-BE2V

HAMPEL, Carrie, 2019. *Airbus and Siemens cooperation cut short.* In electrive.com. Rosenthaler Str. 34/35, 10178 Berlin, Germany Available at: https://www.electrive.com/2019/05/09/airbus-and-siemens-cooperation-cut-short/ archived as: https://perma.cc/3SCM-FDWT

ICAO, 2008. *Aircraft engine emissions, Annex 16 to the Convention on International Civil Aviation - Environmental Protection.* Available at: https://law.resource.org/pub/us/cfr/ibr/004/icao.annex.16.v2.2008.pdf, archived as: https://perma.cc/P4PC-JGTH

ICSA, 2016. *Contribution of the global aviation sector to achieving Paris agreement climate objectives.* International Coalition for Sustainable Aviation. Available at: https://unfccc.int/sites/default/files/resource/156_CAN%20ICSA%20Aviation%20TD%20submission.pdf, archived as: https://perma.cc/84H6-XBB3

IPCC, 1999. *Aviation and the Global Atmosphere.* Intergoverna l Panel on Climate Change. Available at:: https://www.ipcc.ch/report/aviation-and-the-global-atmosphere-2/, archived as: https://perma.cc/USX6-KPSV

JAGGI, Rohit, 2018. *The Electric Airplane Revolution May Come Sooner Than You Think.* In Robb Report. Available at: https://robbreport.com/motors/aviation/eviation-alice-electric-airplane-revolution-sooner-than-you-think-2830522/ archived as: https://perma.cc/NYV6-SXML

KOPPE, Mathias, 2012. *Kraftstoffverbräuche von Turbofan, Propfan und Turboprop im Vergleich.* Hamburg, Germany: HAW Hamburg, project. Available at: http://Library.ProfScholz.de

LAMANCUSA, J. S., 2009. *NOISE CONTROL: Outdoor Sound Propagation*. Available at: https://www.mne.psu.edu/lamancusa/me458/10_osp.pdf ,archived as: https://perma.cc/RU5Z-RBCS

LASAGNA, P. L., Mackall, K. G., Burcham, F. W. and Putnam, T. W., 1976. *Landing approach airframe noise measurements and analysis.* SW Washington, FAA: United States Department of Transportation. Available at: http://www.tc.faa.gov/its/worldpac/techrpt/rd77-29.pdf, archived as: https://perma.cc/KTS7-T27U

LEE, David S., Fahey, David W., Forster, Piers M., Newton, Peter J., Wit, Ron C.N., Lim, Ling L., Owen, Bethan., Sausen, Robert, 2009. *Aviation and global climate change in the 21st century.* Atmospheric Environment 43 (2009) 3520–3537, Elsevier Available at: https://elib.dlr.de/59761/1/lee.pdf, archived as: https://perma.cc/XP23-6NAK

NAP, 2016. *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions.* Washington, D.C: The National Academies Press. Available at: https://doi.org/10.17226/23490

NIŢĂ, Mihaela Florentina, 2013: *Contributions to Aircraft Preliminary Design and Optimization*. München: Verlag Dr. Hut. - ISBN 978-3-8439-1163-4, Dissertation. Available at: http://OPerA.ProfScholz.de

OGP Network, 2018. *Jetsuite launch customer of Zunum hybrid-electric aircraft.* Available at: http://ogpnetwork.com/jetsuite-launch-customer-of-zunum-hybrid-electric-aircraft/, archived as: https://perma.cc/XLW8-M79P

ROSKAM, Jan,1989. *Airplane Design, Pt. 1: Preliminary sizing of airplanes.* Kansas.

RVIM, 2016. *A harmonized life cycle impact assessment method at midpoint and endpoint level.* Netherlands: National Institute for Public Health and the Environment. Available at: https://www.rivm.nl/sites/default/files/2018-11/Report%20ReCiPe_Update_20171002_0.pdf archived as: https://perma.cc/3QGC-R4BH

SARKAR, A. N., 2012. *Evolving Green Aviation Transport System: A Hoilistic Approah to Sustainable Green Market Development.* American Journal of Climate Change, Vol 1 (2012), No. 3, pp. 164-180. Available at: https://file.scirp.org/pdf/AJCC20120300004_46552942.pdf, archived as: https://perma.cc/8VAW-4ZCH

SARSFIELD, Kate, 2019. *Electric aircraft projects to top 200 by year-end: Roland Berger.* Flightglobal. Available at: https://www.flightglobal.com/news/articles/electric-aircraft-projects-to-top-200-by-year-end-r-458135/, archived as: https://perma.cc/EC88-G4JF

SCHOLZ, Dieter, 2019a. *Electric and Hybrid Aviation – From Media Hype to Flight Physics.* Hamburg Aerospace Lecture Series (HALS), Hamburg, 2017-04-25. Available at : https://doi.org/10.5281/zenodo.3265212, archived as: https://perma.cc/RZF6-N2XJ

SCHOLZ, Dieter, 2019b. *Lecture notes of Aircraft Design.* Hamburg, Germany: HAW Hamburg. Available at: http://HOOU.ProfScholz.de

SCHWARTZ, D. Emily, 2011. *Aircraft design for reduced climate impact.* Standford University, PhD. Available at: https://stacks.stanford.edu/file/druid:yf499mg3300/thesis_online_final-augmented.pdf , archived as: https://perma.cc/AB7V-PWH7

SINTEC, 2016. *Conceptos fundamentales del sonido.* Sistemas de insonorización para la industria y el medio ambiente. Available at: http://www.acdacustics.com/files/conceptos.pdf, archived as: https://perma.cc/3RHD-JD6W

SVOBODA, Charlie, 2000. *Turbofan engine database as a preliminary design tool*., University of Kansas: Department of Aerospace Engineering. Available at: https://kundoc.com/pdf-turbofan-engine-database-as-a-preliminary-design-tool-.html, archived as: https://perma.cc/F2L2-5CVQ

TIMMIS, Andrew, 2015. *A stakeholder approach to sustainable development in UK aviation.* Faculty of Social Sciences, Sheffield University Management School, , Sheffield, England, UK. Available at: https://pdfs.semanticscholar.org/3da0/c1dddc7eefe4513586a35d5470bd9acffd5a.pdf, archived as: https://perma.cc/MX6U-ELH9

VAN ENDERT, Lynn, 2017. *Definition of an Ecolabel for Aircraft.* Hamburg, Germany: HAW Hamburg, project. Available at: http://Library.ProfScholz.de

VOLOCOPTER, 2019. *Pioneering the urban air taxi revolution.* Bruchsal, Germany. Available at: https://press.volocopter.com/images/pdf/Volocopter-WhitePaper-1-0.pdf, archived as: https://perma.cc/S3AX-5SDB

WAYSON, Roger L., Fleming, Gregg G. and Iovinelli, Ralph, 2009. *Methodology to estimate particulate matter emissions from certified commercial aircraft engines.* Journal of the Air & Waste Management Association. Available at:

https://www.tandfonline.com/doi/pdf/10.3155/1047-3289.59.1.91?needAccess=true, archived as: https://perma.cc/UD5W-5BLJ

WHO, 2014, *7 million premature deaths annually linked to air pollution.* World Health Organization. Available at: https://www.who.int/mediacentre/news/releases/2014/air-pollution/en/ archived as: https://perma.cc/HS7K-KZRH

YIN, Feijia and Gangoli, Arvind R., 2016. *Performance assessment of a Multi-fuel Hybrid Engine for Future Aircraft.* Delft University of Technology. Available at: http://pure.tudelft.nl/ws/files/7745732/Performance_assessment_of_a_Multi_fuel_Hybrid_Engine_for_Future_Aircraft.pdf, archived as: https://perma.cc/RM5K-N3L8

# Acknowledgments

This master thesis could not have been done without the help of Dieter Scholz. Thanks for receiving me in a foreign country, and giving me the opportunity of working with you, despite you did not know who I was before going to Hamburg. Thanks for believe in my skills and support all my work. The first weeks I felt so nervous and lost, but you made it possible for me to find my path through this master thesis. I have learned a lot about the aeronautical world. Working with you have been a pleasure. Thank you very much.

My master thesis friends, Brecht Caers and Clinton Rodrigo, also deserve a space in the acknowledgments. Without you, this master thesis would probably be less accurate. So many evenings exchanging information and ideas, helping to improve the master thesis of each other, and having coffees. You have been a really nice colleagues, and for me it has been a pleasure meeting you and working with you.

I also have to be grateful with the HAW University of Hamburg. Keep promoting the ERASMUS program. Going on an ERASMUS exchange is one of the best things a student can do. This university received me with open arms, and also helped me during my integration in the Hamburg lifestyle. Thanks for made everything easier for me.

Back to my home university, I have to be grateful with all the people that made possible the end of my master. All the people who worked with me during this two years. People whit whom I spent so many stressful moments, exams failure, but also success and, sometimes, happiness. Special mention to Javier Indave Sotillos. Our path in the university is over, but the path of the life begins.

Of course I have to say thanks to my family. Thanks for pushing me into the moving in Hamburg. Thanks for cheering me up always, no matter the problem and situation. Thanks for being always there. Thanks for made me be the person who I am right now.

It is not possible to mention all the people that, somehow, helped me during this master thesis. I have been surrounded of such an amazing people, and the only thing I can say is thanks. Thanks to everybody.