Politecnico di Milano

SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

Master of Science Course in Aeronautical Engineering

Market and Cost Analysis of Hybrid-Electric Aircraft

Supervisor: Prof. Lorenzo TRAINELLI
Co-supervisor: Prof.ssa Elena PELLIZZONI

Master of Science Thesis of:
Raouf IBRAHIM
Matr. 864652

Accademic Year 2017–2018

Ringraziamenti

Desidero ringraziare tutti coloro che hanno contribuito al raggiungimento di questo importante traguardo e alla stesura del suo atto finale.

Ringrazio il relatore, il prof. Lorenzo Trainelli, e il co-relatore, la prof.ssa Elena Pellizzoni, che insieme al prof. Alberto Rolando e al prof. Carlo E. D. Riboldi, oltre ad avermi guidato nello svolgimento di questo lavoro sono stati fonte di conoscenza durante il percorso universitario. La mia riconoscenza va, inoltre, al dott. Francesco Salucci, dottorando del Politecnico di Milano, che è sempre stato disponibile per discutere dei risultati, chiarire i dubbi e fornire suggerimenti.

Un grande ringraziamento va alle persone che mi hanno supportato e sopportato durante questi anni. Ai miei genitori, Mona e Rimon, che con il loro instancabile sostegno e le loro ininterrotte preghiere, mi hanno permesso di arrivare fin qui, contribuendo alla mia formazione personale.

A mia sorella Rosa e la mia fidanzata Elena, che hanno affrontato insieme a me questo cammino, passo dopo passo, giorno dopo giorno, sacrificio dopo sacrificio, superando tutte le difficoltà e sconfitte e festeggiando insieme ogni vittoria.

Infine, un grazie speciale va a Dio, per essere stato sempre al mio fianco.

Abstract

This thesis analyzes the manufacturing and operating costs of a hybrid-electric micro-feeder starting from a solid market analysis. The work focuses on establishing a model for evaluating the market implementation of future hybrid-electric transport airplanes. Current European plans for future aviation involve a major effort in the reduction of both noise and pollutant emissions from airplanes. Among habilitating factors, various personal air transportation concepts based on electric or hybrid-electric are currently being developed, and several aircraft manufacturers have achieved the required capabilities to design and build two- and four-seater electric or hybrid-electric aircraft. The introduction of a larger aircraft of this type may have the potential to impact heavily on commercial aviation and on the quality of life of European citizens at large. In particular, a micro-feeder intended as a small commuter aircraft providing a shuttle service from minor airports, and even airfields, towards major hubs, can boost air transportation, easing travel within the European Union and offering a solution to low-infrastructured areas, while being eco-sustainable. The analysis is composed of two major phases. The market analysis estimates the potential demand of the aircraft of interest. This analysis follows three steps. In the first, each country's transportation system is analyzed. This allows defining an index representing the "transportation system efficiency" of each country. The second step exploits the trans-European transport network defined by EU commission to identify the main EU airports. Finally, the third step estimates the volume of potential users. These are evaluated by identifying all the candidate routes for the micro-feeder service, obtained through adequate filtering. The cost analysis evaluates the production costs and operating costs. This analysis targets two different points of view: manufacturing and operations. Both rely on modified existing models, such as DAPCA-IV, Gudmunsson, Eastlake and Sforza We assume a specific aircraft as the candidate vehicle for the micro-feeder service, through its main performance and design specification, based on a previous preliminary sizing activity.

Keywords:
hybrid-electric aircraft; market analysis; cost analysis; production costs; operative costs.

Sommario

Questa tesi analizza i costi di produzione e operativi di un micro-feeder ibrido-elettrico partendo da una solida analisi di mercato. Il lavoro si focalizza sulla creazione di un modello per valutare l'implementazione di velivoli da trasporto ibrido-elettrici nel vicino futuro. Gli attuali piani europei per il futuro dell'aviazione, comportano uno sforzo importante nella riduzione delle emissioni degli aerei, sia di rumore che di sostanze inquinanti. Sono attualmente in fase di sviluppo vari progetti di velivoli elettrici o ibrido-elettrici, e diversi produttori di aeromobili hanno raggiunto le capacità necessarie per progettare e costruire tali velivoli con la realizzazione di modelli da due e quattro posti. L'introduzione di un aeromobile più grande con queste caratteristiche potrebbe avere un impatto significativo sull'aviazione commerciale e sulla qualità della vita in Europa. In particolare, un micro-feeder, inteso come un piccolo velivolo che fornisce un servizio navetta da aeroporti minori verso i principali hub, può aumentare il flusso di passeggeri, facilitare i viaggi all'interno dell'Unione Europea e offrire un maggiore servizio alle aree periferiche, salvaguardando l'ambiente. La seguente analisi è composta da due fasi principali: un'analisi di mercato e un'analisi costi-benefici. L'analisi di mercato stima la potenziale domanda di un servizio di micro-feeder. Questa analisi segue tre step. Nel primo, viene analizzato il sistema di trasporto di ogni singolo paese europeo. Ciò consente di definire un indice che rappresenti "l'efficienza del sistema di trasporto" di ciascun paese. Il secondo passaggio sfrutta la rete di trasporti transeuropea definita dalla commissione UE per identificare i principali aeroporti europei. Infine, il terzo step stima il volume dei potenziali utilizzatori del servizio. Questi vengono valutati identificando tutte le rotte candidate per il servizio di micro-feeder, ottenute attraverso un adeguato filtraggio di tutte le rotte disponibili. L'analisi dei costi valuta i costi di produzione e i costi operativi. Questa analisi viene condotta da due diversi punti di vista, quella del produttore e quella dell'operatore. Entrambi si basano su modelli matematici esistenti, come il DAPCA-IV e quelli dei professori Gudmunsson, Eastlake e Sforza, ma adattati al nostro studio. In questa tesi viene preso come riferimento per il servizio di micro-feeder uno specifico modello, le cui principali prestazioni e specifiche di progettazione sono state stimate precedentemente in un altro studio.

Parole chiave:
aeromobile ibrido-elettrico; analisi di mercato; analisi dei costi; costi di produzione; costi operativi.

Contents

List of Figures **ix**

List of Tables **x**

Nomenclature **xii**

1 Introduction **1**

1.1 EUROPE 2020 1

1.2 Flightpath 2050 2

1.3 MAHEPA project 4

1.4 Motivation 5

2 State of the art **9**

2.1 Environmental impact of pollutant emissions 9

2.1.1 Nitrogen oxides 10

2.1.2 Carbon dioxide 11

2.1.3 Other Pollutants 12

2.2 Environmental impact of noise emissions 14

2.3 Hybrid-Electric aircraft 16

2.3.1 Products, prototypes and concepts 18

2.4 Models for cost estimation 18

3 Market Analysis **23**

3.1 European transportation data analysis 24

3.1.1 Motorways 25

3.1.2 Railways 28

3.1.3 Data analysis 28

3.2 Identification of the main nodes 34

3.2.1 Trans-European Transport Network TEN-T 34

3.2.2 The comprehensive network 36

3.2.3 The core network 37

3.3 Route analysis . . . 41
3.3.1 Database creation . . . 41
3.3.2 Initial analysis . . . 43
3.3.3 Comparison with competitors . . . 45
3.3.4 Isoline maps . . . 46
3.4 Demand estimation . . . 50
3.5 Case studies . . . 52

4 Cost analysis **57**
4.1 Time planning . . . 58
4.2 Manufacturer costs . . . 63
4.2.1 Adaptation of cost estimation models . . . 63
4.2.2 Development cost estimation of a hybrid-electric micro-feeder 67
4.3 Investment appraisal . . . 77
4.4 Operator costs . . . 82

5 Conclusions **87**
5.1 Outcomes . . . 87
5.2 Future developments . . . 90

Bibliography **91**

List of Figures

1.1 Conceptual map of the present work 7

2.1 Emissions from a typical two-engine jet aircraft 10
2.2 Aircraft NO_x emissions 1990-2035 11
2.3 Aircraft CO_2 emissions 1990-2035 12
2.4 Example of notional airport noise contours 14
2.5 Noise emissions 2005-2035 15
2.6 Noise emissions and pollutants emissions forecast 2005-2035 15
2.7 Hybrid-Electric trend over the next 40 years 16

3.1 Motorway network density per country 27
3.2 Railway network density per country 31
3.3 Ground transportation network density per country 33
3.4 TEN-T core and comprehensive airports map 38
3.5 Door to door travel using three modes of transportation 47
3.6 Isoline map examples 50
3.7 Ground transportation network density per case studies 53
3.8 Route filtering steps scheme 55

4.1 Elementary outline of an aircraft project development timeline . . . 61
4.2 Cost breakdown structure 62
4.3 Net Cash Flow 79

List of Tables

2.1 Summary of emission indicators based on IMPACT data 13
2.2 Summary of noise indicators 13
2.3 Summary of flyable manned hybrid and electric aircraft 20
2.4 Summary of electric fixed-wing aircraft concepts and studies 21

3.1 Motorway network length and density per country 26
3.2 Ground transportation network density classification 29
3.3 Railway network length and density per country 30
3.4 Ground transportation network density per country 32
3.5 List of the major airports (core network) 39
3.6 List of the minor airports (comprehensive network) 40
3.7 Hybrid-electric micro-feeder performances and design specifications . 42
3.8 Volume of the annual potential market for each case studies 54

4.1 Comprehensive list of the costs classified in analogic, reshaped and ad hoc 65
4.2 Input values for costs estimation for a hybrid-electric micro-feeder . 74
4.3 Cost estimation per important areas of the project 74
4.4 Cost estimation per year per important areas of the project 75
4.5 Cost estimation per year per important areas of the project 76
4.6 Cost estimation per year per important areas of the project (from the start date to 7th) 80
4.7 Cost estimation per year per important areas of the project (from 8th year to the 15th) 81

Nomenclature

Notation

AIP	Annual international air passengers
AP	Annual air passengers
AP	Wing Aspect Ratio
C_{AC}	Unit cost of the aircraft [€]
C_{ACin}	Insured valued of aircraft [€]
$C_{ACdepre}$	Aircraft specific depreciation costs [€]
$C_{BATdepre}$	Battery specific depreciation costs [€]
C_{ele}	Electricity cost [€/kWh]
C_{FLOW}	Cash flow [€]
C_{fuel}	Fuel cost [€/kg]
C_{IN}	Cash in flow [€]
C_{OUT}	Cash out flow [€]
C_{AM}	Annual maintenance cost [€/yr]
C_{AMac}	Annual aicrcraft maintenance cost [€/yr]
C_{BAT}	Battery cost [€/kWh]
C_{CERT}	Total cost for certification [€]
C_{CONV}	Exchange from dollar to euro
C_{CREW}	Crew cost [€/hr]
C_{DEV}	Total development support cost [€]

C_{ENG}	Total cost of engineer [€]
C_{energy}	Total energy costs [€]
C_{EG}	Cost of electric generator [€]
C_{EM}	Cost of electric motor [€]
C_{FT}	Total cost for flight test operations [€]
C_{FUEL}	Annual fuel cost [€/yr]
C_{FEES}	Annual fees [€/yr]
C_{GRND}	Ground operation fees [€/yr]
C_{HR}	Cost per flight hour [€/hr]
C_{INS}	Annual cost for insurance [€/yr]
C_{INSP}	Annual inspection cost [€/yr]
C_{LOAN}	Monthly loan payment [€/month]
C_{LND}	Landing fees [€/yr]
C_{MAT}	Total material cost [€]
C_{MFG}	Total manufacturing cost [€]
C_{OVER}	Annual engine overhaul [€/yr]
CPI	Consumer Price Index
C_{PP}	Cost of engine [€]
C_{QC}	Total cost of quality control [€]
C_{SGA}	Cost for selling, general and administration [€]
C_{STOR}	Cost for storage [€]
C_{TOOL}	Total tooling cost [€]
C_{YEAR}	Yearly operational cost [€]
d	Distance between two points on a sphere
d_{ops}	Average operational distance [km]
d_{range}	Range [km]

D	Discount factor
e_b	Battery Specific Energy [kWh/kg]
E_{bat}	Battery Energy [kWh]
f_{comp}	Fraction of airframe made from composites
F_{CERT}	Certification factor
F_{CF}	Flap system factor
F_{COMP}	Factor to account for the use of composites in the airframe
F_{EXP}	Experience effectiveness factor
F_{burn}	Fuel burn [kg]
F_{HYB}	Hybridization factor
F_{MF}	Required maintenance manhours for every flight hour
F_{PRESS}	Pressurization factor
F_{TAPER}	Chord taper factor
hav	Haversine
h_{ops}	Utilization hours per year [hrs/yr]
H_{ENG}	Number of engineering manhours [hr]
H_{MFG}	Number of manufacturing labor hours [hr]
H_{TOOL}	Number of tooling man-hours [hr]
k_{nav}	Navigation fee factor
$MTOW$	Maximum take-off weight [kg]
N	Number of units produced (context-dependent)
N	Number of planned aircraft to be produced (context-dependent)
N_{BATc}	Lifetime cycles of the batteries
N_{BE}	Number of sold units to break-even
N_{CREW}	Number of crew members to operate aircraft
N_{ENG}	Number of engineers

N_{flight}	Flight cycles per year
N_{PL}	Number of payload
N_{PROT}	Number of prototypes
N_{PP}	Number of engines
p_{HYB}	Degree of hybridization (power of the electric propulsion with respect to the total installed power)
P_{AC}	Unit price of the aircraft [€]
$P_{EM,max}$	Maximum power of the electric motor [kW]
$P_{TM,max}$	Maximum power of the thermal motor [kW]
$P_{Total,max}$	Maximum total power [kW]
Q_{FLGT}	Flight hours per year [hrs/yr]
Q_m	Aircraft production rate
r	Radius of a sphere
R_{AP}	Rate for certified Airframe and Power plant mechanic [€/hr]
R_{CREW}	Rate for crew [€/hr]
R_{ENG}	Rate of engineering labor [€/hr]
R_{FUEL}	Cost of fuel [€/gal]
R_{INSP}	Inspection rate [$]
R_{MFG}	Rate of manufacturing labor [€/hr]
R_{STOR}	Rate for storage [€/yr]
R_{TOOL}	Rate of tooling labor [€/hr]
RES	Number of residents
t_{am}	The time spent in air maneuvering [hr]
t_{Amfg}	Average to manufacture a single unit [hr]
t_{block}	Block time per operational mission
t_c	The time spent in the climb [hr]

t_{cr}	The cruise time [hr]
t_d	The time spent in the descent [hr]
t_{eol}	Aircraft life expectancy [hr]
t_{gm}	Ground maneuver time [hr]
t_{AB}	Travel time by car from A to C [min]
t_{AC}	Travel time by car or train from A to C [min]
t_{BC}	Micro-feeder travel time from B to C [min]
T	Rated thrust [$\mathrm{lb_f}$]
T/W	Thrust-to-weight ratio
V_H	Maximum speed in level flight in KTAS [ft/s]
W	Weight [$\mathrm{lb_f}$]
$W_{airframe}$	Weight of structural skeleton [$\mathrm{lb_f}$]

β	Annual international passengers fraction between major airport and relative country
λ_1	Longitude of point 1
λ_2	Longitude of point 2
φ_1	Latitude of point 1
φ_2	Latitude of point 2
θ	Generic Angle
Θ	Central Angle between two points on a sphere

Acronyms

A/C	Aircraft
AOL	Aircraft Operating Limitations
ATC	Actualization
AC	Accounts Receivable
AP	Accounts Payable
BEV	Battery Electric Vehicle
CAEP	Committee on Aviation Environmental Protection
CAPEX	CAPital EXpenditure
CERs	Cost Estimating Relationships
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CPI	Consumer Price Index
DAPCA	Development And Procurement Costs of Aircraft
DNCF	Discounted Net Cash Flow
DC	Direct Costs
DoH	Degree of Hybridization
EASA	European Aviation Safety Agency
EBIT	Earning Before Interest and Taxes
EEA	European Environment Agency
EFTA	European Fair Trade Association
END	Environmental Noise Directive
EPSON	European Spatial Planning Observatory Network
EU	European Union
EU ETS	European Emissions Trading System
EV	Electric Vehicle

FAA	Federal Aviation Administration
FC	Fuel Cell
FE	Full Electric
FL	Flight Level
GA	General Aviation
HC	Hydrocarbon
HEA	Hybrid-Electric Aircraft
HEV	Hybrid-Electric Vehicle
HTS	High-Temperature Superconductors
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICE	Internal Combustion Engine
KTAS	Knots True AirSpeed
ISTAT	Italian National Institute of Statistics
LTO	Landing and Take-Off
MAHEPA	Modular Approach to Hybrid-Electric Propulsion Architecture
MEGA	Metropolitan European Growth Area
MFTS	Master Flight Test Schedule
MTOW	Maximum Take-Off Weight
NPV	Net Present Value
NCF	Net Cash Flow
NUTS	Nomenclature of Territorial Units for Statistics
PHE	Parallel Hybrid Electric
POC	Proof-Of-Concept
POH	Pilots' Operating Handbook
PV	Present Value

QDF	Quantity Discount Factor
RDTE	Research, Development, Test and Evaluation
SGA	Selling General and administration
SHE	Series Hybrid Electric
STAPES	SysTem for AirPort noise Exposure Studies
T/O	Take-off
TE	Turbo Electric
TEN-T	Trans-European Transport Network
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
WACC	Weighted Average Cost of Capital

Chapter 1

Introduction

1.1 EUROPE 2020

Europe faces a moment of transformation. The crisis has wiped out years of economic and social progress and exposed structural weaknesses in Europe's economy. In the meantime, the world is moving fast and long-term challenges – globalization, pressure on resources, aging – intensify. Europe is now searching for a strategy to help itself come out stronger from the crisis and turn the EU into a smart, sustainable and inclusive economy delivering high levels of employment, productivity, and social cohesion. Europe 2020 sets out a vision of Europe's social market economy for the 21st century. Europe 2020 puts forward three mutually reinforcing priorities:

- Smart growth: developing an economy based on knowledge and innovation.
- Sustainable growth: promoting a more resource efficient, greener and more competitive economy.
- Inclusive growth: fostering a high-employment economy delivering social and territorial cohesion.

The EU needs to define where it wants to be by 2020. To this end, the Commission proposes the following EU headline targets:

- 75% of the population aged 20-64 should be employed.
- 3% of the EU's GDP should be invested in R&D.
- The "20/20/20" climate/energy targets should be met (including an increase to 30% of emissions reduction if the conditions are right).
- The share of early school leavers should be under 10% and at least 40% of the younger generation should have a tertiary degree.

- 20 million fewer people should be at risk of poverty.

The Commission proposes that EU goals are translated into national targets and trajectories. The targets are representative of the three priorities of smart, sustainable and inclusive growth but they are not exhaustive: a wide range of actions at national, EU and international levels will be necessary to underpin them. The Commission is putting forward seven flagship initiatives to catalyze progress under each priority theme. Of particular interest for the present work is the one concerning energy::

> "Resource efficient Europe" to help decouple economic growth from the use of resources, support the shift towards a low carbon economy, increase the use of renewable energy sources, modernize our transport sector and promote energy efficiency.

The targets must also be measurable, capable of reflecting the diversity of Member States situations and based on sufficiently reliable data for purposes of comparison. For this reason, the just quoted initiative is translated into a reduction of greenhouse gas emissions by at least 20% compared to 1990 levels, the increase of the share of renewable energy sources in our final energy consumption to 20% and a 20% increase in energy efficiency

EU-level instruments, notably the single market, financial levers, and external policy tools, will be fully mobilized to tackle bottlenecks and deliver the Europe 2020 goals.

1.2 Flightpath 2050

As previously stated, Europe is entering a new age where it faces many challenges such as globalization, a financial system in need of reform, climate change and an increasing scarcity of resources. Aviation is a catalyst for growth and skilled employment. As such, it is at the heart of the EUROPE 2020 strategy. This is why the European air transport system is directly concerned by new challenges regarding its competitiveness, performance, and sustainability.

Flightpath 2050 is an ambitious vision for aviation promoted by the European Commission and many key stakeholders of European aviation from the aeronautics industry, air traffic management, airports, airlines, energy providers and the research community. The strategy addresses customer orientation and market needs as well as industrial competitiveness and the need to maintain adequate skills and a research infrastructure based in Europe. By 2050, passengers and freight should enjoy efficient and seamless travel services, based on a resilient air transport system thoroughly integrated with other transport modes and well connected to the rest of the world. This will be necessary in order to meet the growing demand for travel. It must also help to reduce aviation's impact on citizens and the environment. Aviation has an important role to play in reducing noise as well as greenhouse gas emissions, regardless of traffic growth.

Aviation is a vital facilitator of European integration and cohesion by providing essential transport links. It is an important enabler of prosperity and wealth creation for the Member States and their peripheral regions by stimulating development, opening new markets, boosting international trade and encouraging companies to invest.

It is also important to underline that on average, 12% of aeronautic revenues, representing almost €7 billion per year for civil aeronautics alone, are reinvested in Research and Development (R&D) and support around 20% of aerospace jobs. Every euro invested in aeronautics R&D creates an equivalent additional value in the economy every year thereafter. Aeronautical technologies are catalysts for innovation and spill-over into other economic and technological sectors, thus contributing to the growth of the European economy as a whole. The aviation sector is also fully aware of its responsibilities towards Europe's citizens: protection of the environment, security and safety. It is meeting these challenges successfully and so enabling its continued contribution to European economic and societal well-being.

However, the industrial competition is becoming ever fiercer from established, traditional rivals such as the US and even more so from new and strong challengers, notably Brazil, Canada, China, India and Russia. Europe must succeed despite this increased competition. For that to happen, Europe must address three key challenges: increase the level of technology investment, enhance its competitiveness in world air transport markets and accelerate the pace of policy integration. Technological leadership, the root of Europe's current success, will continue to be the major competitive differentiator. Break-through technology will be required to secure a future competitive advantage, most notably in terms of energy, management of complexity and environmental performance. Substantial and sustained investment in the technologies of today and tomorrow is needed to guarantee the future, as well as readiness to spin-in advances arising from defense investment where appropriate.

Europe must seize the opportunity of the expanding aviation market, and preserve its pre-eminent position to ensure the continued success and economic contribution of its aviation industry in European and export markets. Building on the vision for 2020, and the ensuing ACARE initiative, flightpath2050 lays out the vision for European aviation to 2050.

It includes several goals [43]:

- 90% of travelers within Europe are able to complete their journey, door-to-door within 4 hours. Passengers and freight are able to transfer seamlessly between transport modes to reach the final destination smoothly, predictably and on-time;
- an air traffic management system is in place that provides a range of services to handle at least 25 million flights a year of all types of vehicles, (fixed-wing aircraft, rotorcraft) and systems (manned, unmanned, autonomous) that are integrated into and inter-operable with the overall air transport system with 24-hour efficient operation of airports;
- flights arrive within 1 minute of the planned arrival time regardless of weather conditions. The transport system is resilient against disruptive events and is capable of automatically and dynamically reconfiguring the journey within the network to meet the needs of the traveler if disruption occurs;
- a coherent ground infrastructure is developed including airports, vertiports and heliports with the relevant servicing and connecting facilities, also to other modes.

In this vision, protecting the environment and the energy supply is a key element. Alongside the above goals, Flightpath includes several environmental goals:

- technologies and procedures available allow a 75% reduction in CO_2 emissions per passenger kilometer and a 90% reduction in NO_x emissions. The perceived noise emission of flying aircraft is reduced by 65%. These are relative to the capabilities of typical new aircraft in 2000;
- aircraft movements are emission-free when taxiing;
- air vehicles are designed and manufactured to be recyclable;
- Europe is established as a center of excellence on sustainable alternative fuels, including those for aviation, based on a strong European energy policy;
- Europe is at the forefront of atmospheric research and takes the lead in the formulation of a prioritized environmental action plan and establishment of global environmental standards.

1.3 MAHEPA project

Modular Approach to Hybrid-Electric Propulsion Architecture (MAHEPA) is a European research project that aims to overcome the limits of electric-powered airplanes by introducing two new hybrid electric powertrains to enable cleaner, quieter and more efficient aircraft propulsion. By adopting a modular approach to propulsion system component design, two variants of a serial hybrid-electric powertrain will be tested in flight for the first time. The first aircraft will be equipped with a propulsion system that uses an internal combustion engine, while the second will have a hybrid fuel cell system, which will demonstrate the possibility offered by this technology to fly at zero emissions over long distances. The first flight is scheduled for 2020. MAHEPA is developing key technologies and a roadmap for market implementation of future hybrid-electric airplanes. They will ensure air transport that is both economical and sustainable. The project involves aircraft manufacturers, companies and universities, including *Politecnico di Milano*. This thesis contributes to the project studies concerning the scenario for future short-haul air transportation using hybrid-electric aircraft.

1.4 Motivation

All the mentioned goals are not likely to be achieved with an incremental innovation, i.e. with the continuous improvements of conventional technologies: current technology has already been pushed to the edge. Indeed, a radical innovation is required to satisfy the key objectives mentioned in EUROPE2020 and in Flightpath2050. Among the new aircraft concepts or systems considered for development, there is the hybrid-electric aircraft, that promises to lower emissions and noise pollution. The idea of implementing an electric or hybrid-electric air shuttle service is almost a reality and different aircraft manufacturers have achieved the required capabilities to design and build two and four-seater electric aircraft. The introduction of a larger electric or hybrid-electric aircraft has the potential to revolutionize a large portion of air transport.

The adoption of this new technology is bounded to its cost-effectiveness. The transition to hybrid-electric aircraft is subjected to the price of new elements: batteries, power plant, chargers and electricity. If their cost is paid back by the lower fuel consumption, the aircraft owner obtains a profit. This, combined with a reduced environmental impact, would open the door to the spread of such an aircraft.

This thesis addresses an analysis of the costs involved in the production of hybrid-electric aircraft fleet. This is based on a solid market analysis to estimate the potential demand of the aircraft of interest. To date, there is actually a lack in the literature regarding this topic. Compared to the automotive industry, where electrically driven vehicles are a reality, aviation has a delay. In order to cover for this lack of literature, this work establishes a model for evaluating the costs by adapting methods proposed by the literature.

Figure 1.1 presents a schematic conceptual map of this work.

The present work starts with the study of the environmental impact of pollutant emissions, the impact of noise emission and a brief presentation of the available technologies and relative trends, discussed in Chapter 2. The core of the analysis is composed of two major phases. In Chapter 3 the market analysis estimates the potential demand of the aircraft of interest. There is the description of the methodology implemented to estimate it. This is based on different steps:

- a data analysis of the actual state of each European country's transportation system;
- the identification of the main nodes and the main networks inside each country;
- the identification of all the flyable routes.

The estimation of the potential market is done through a procedure implemented in a MATLAB® code. The output of the market analysis is the primary input of the following step, the cost analysis. As a consequence of the amount of computing power requested to evaluate the volume of potential users, it has been done only for three case studies. However, thanks to the method used to choose them the results can be extended to all Europe including any precautions to be taken. The cost analysis is discussed in Chapter 4. It evaluates the production costs and the operating costs targeting two different points of view: manufacturing and operations. In the former, it has been determined the investment that the manufacturing company should sustain to produce a defined quantity of aircraft to cover the volume of the potential market evaluated in the previous step. This is done involving in input an existing model implemented through statistical regression data. The equations of this model have been modified by the author for use as a tool for hybrid-electric design case. The equations have been programmed in MATLAB®. The latter point of view assesses the operating costs that will be met by an operator of the micro-feeder service through a presentation of an implemented model. The operating cost model uses existing computation steps for the conventional operating phases and an implemented procedure based on actual experience of aircraft ownership. The work ends in Chapter 5, where a summary about what has been observed by literature and what has been obtained in previous chapters is presented.

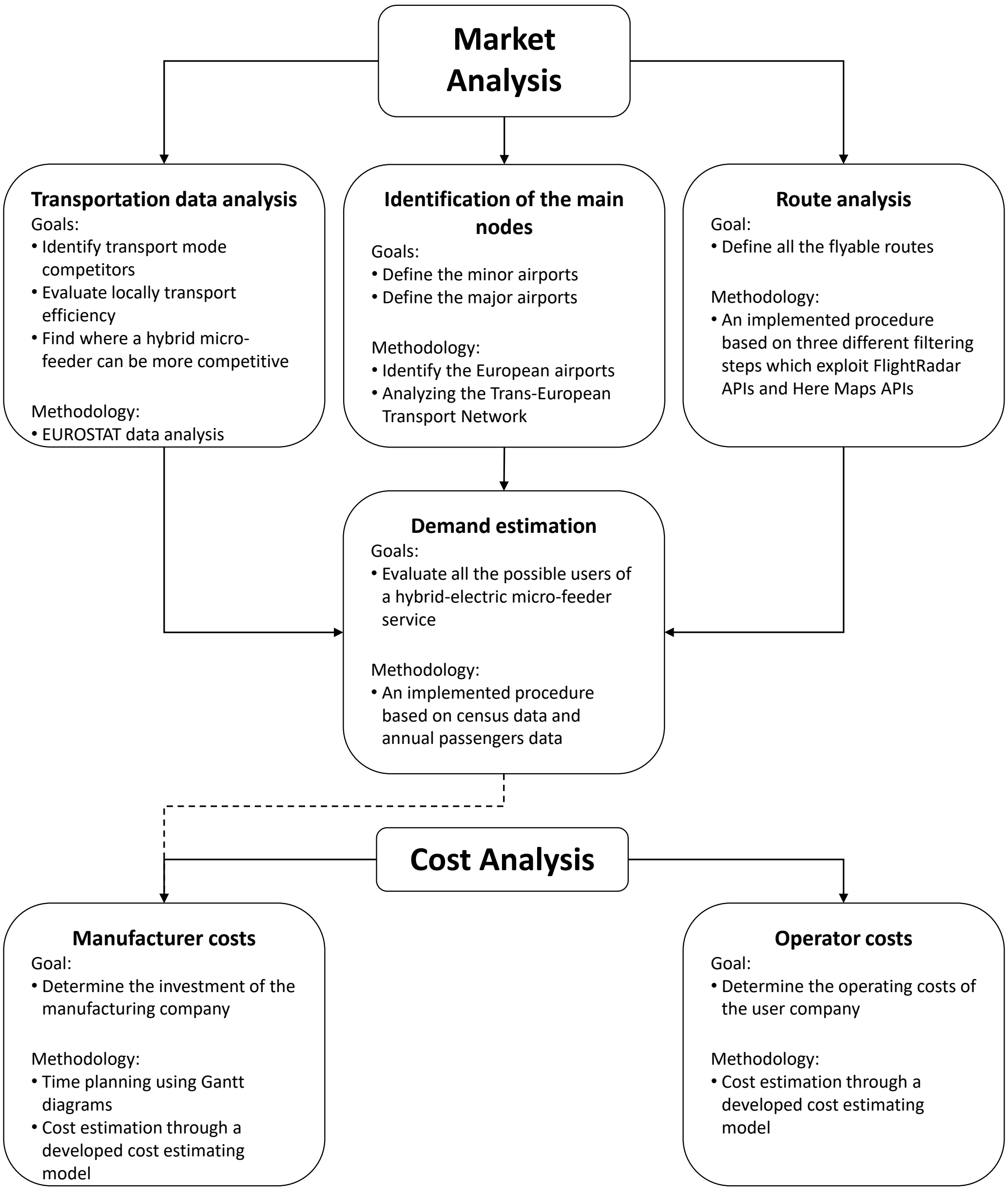


Figure 1.1: Conceptual map of the present work

Chapter 2

State of the art

2.1 Environmental impact of pollutant emissions

At present, the vast majority of vehicles rely on the combustion of Hydrocarbon (HC) fuels to derive the energy necessary for their propulsion. Combustion is a reaction between the fuel and the air that releases heat and combustion products. The heat is converted to mechanical power by an engine, and the combustion products are released into the atmosphere. An HC is a chemical compound with molecules made up of carbon and hydrogen atoms. Ideally, the combustion of an HC yields only carbon dioxide and water, which do not harm the environment. Indeed, green plants "digest" carbon dioxide by photo-synthesis. Carbon dioxide is a necessary ingredient in vegetal life. Animals do not suffer by breathing carbon dioxide unless its concentration in air is such that oxygen is almost absent. The combustion of HC fuel in combustion engines is never ideal. Besides carbon dioxide and water, the combustion products contain a certain amount of nitrogen-oxides (NO_x), carbon monoxides (CO), sulphur oxides (SO_x), and unburned HCs, all of which are toxic to human health. These are the main aircraft engine emission pollutants. They are considered here in Figure 2.1 in terms of a Landing and Take-Off (LTO) cycle of a conventional aircraft below 3,000 ft for local air quality purpose.

Recently, the research and development activities related to transportation have emphasized the development of high-efficiency, clean, and safe transportation. Electric Vehicle (EV), Hybrid-Electric Vehicle (HEV), and fuel cell vehicles have been typically proposed to replace conventional vehicles in the near future.

Technological and operational measures alone are not considered sufficient to tackle the growing environmental challenges of the aviation sector.

The European Union (EU) introduced some market-based measures as part of its comprehensive approach to reduce aviation-related emissions. The EU has successfully implemented the European Emissions Trading System (EU ETS), which

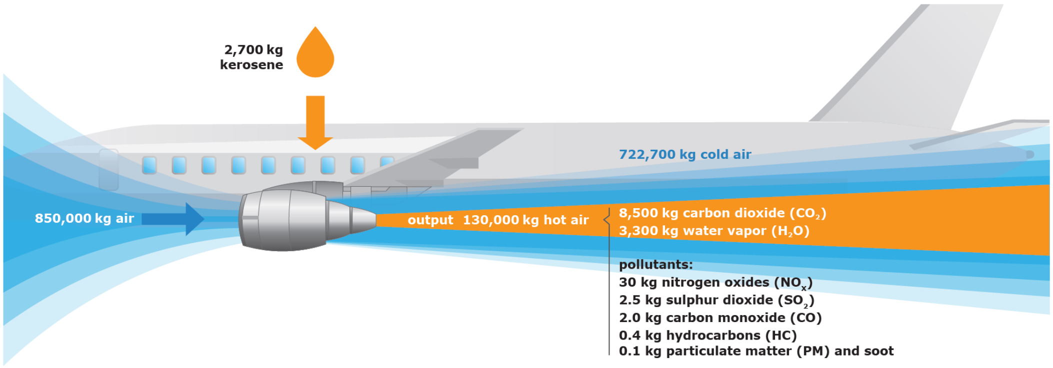


Figure 2.1: Emissions from a typical two-engine jet aircraft during 1-hour flight with 150 passengers [9]

currently covers all intra-European flights. It is the world's first major carbon market and remains the biggest one. The EU ETS will contribute to an annual emission reduction of approximately 16 million tonnes, achieved partly within the sector itself or in other sectors. More than 100 airports in Europe have also deployed noise and emissions charges schemes since the 1990s. In this section, the current and upcoming European pollution policies are reported, showing that aviation is required to lower its environmental impact to reach the emissions goals, as well as to mitigate the pollution economic impact.

2.1.1 Nitrogen oxides

Nitrogen oxides (NO_x) result from the reaction between nitrogen in the air and oxygen. Theoretically, nitrogen is an inert gas. However, the high temperatures and pressures in engines create favorable conditions for the formation of nitrogen oxides. Temperature is by far the most important parameter in nitrogen oxide formation. The most commonly found nitrogen oxide is nitric oxide (NO), although small amounts of nitric dioxide (NO_2) and traces of nitrous oxide (N_2O) are present. Once released into the atmosphere, NO reacts with oxygen to form NO_2. This is later decomposed by the Sun's ultraviolet radiation back to NO and highly reactive oxygen atoms that attack the membranes of living cells. Nitrogen dioxide is partly responsible for smog; its brownish color makes smog visible. It also reacts with atmospheric water to form nitric acid (HNO_3), which dilutes in rain. This phenomenon is referred to as "acid rain" and is responsible for the destruction of forests in industrialized countries. Acid rain also contributes to the degradation of historical monuments made of marble.

NO_x emissions have also increased significantly +85% (316 to 585 thousand tonnes) between 1990 and 2005 according to the Convention on Long-Range Transboundary Air Pollution (CLRTAP) data from the United Nations Economic Com-

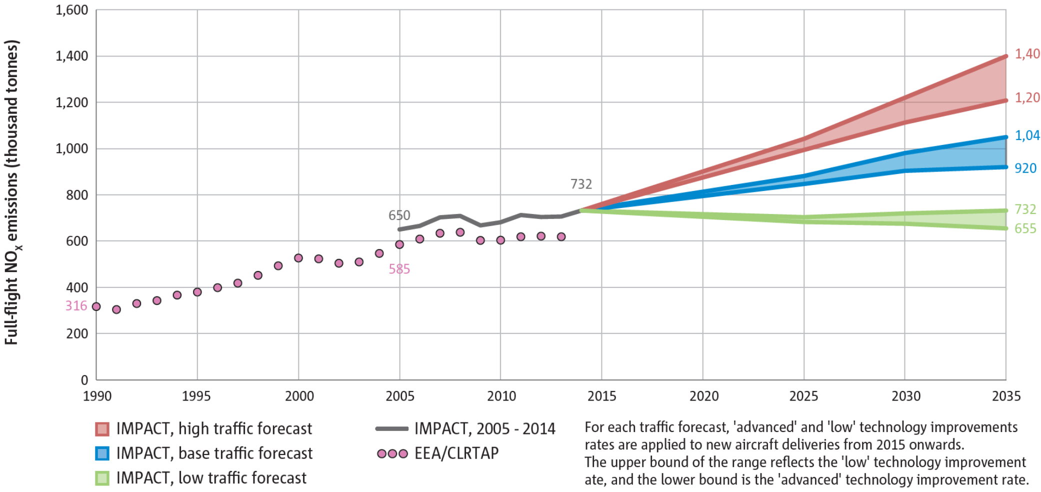


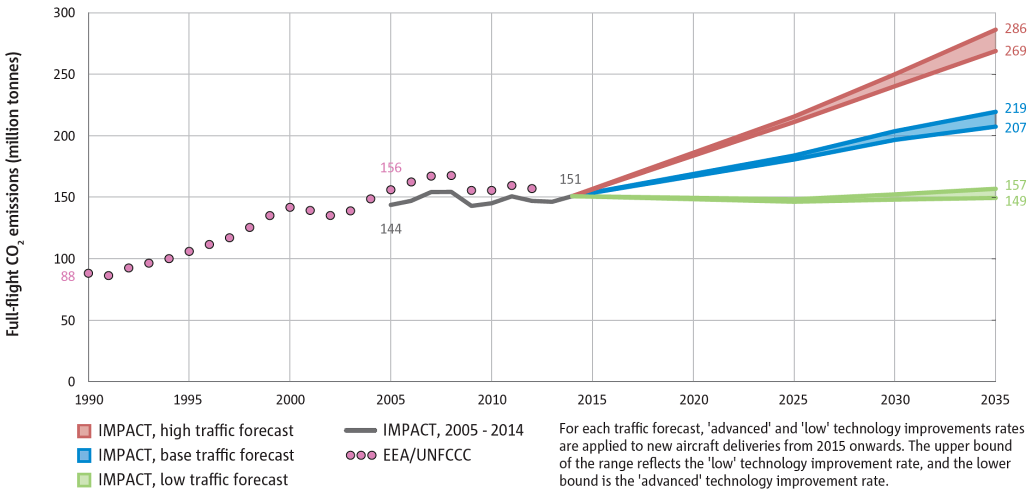
Figure 2.2: Aircraft NO$_x$ emissions forecast [3, 25]

mission for Europe (UNECE), and +13% between 2005 and 2014 according to IMPACT [25] data. Under the base air traffic forecast and assuming an advanced NO$_x$ technology improvement rate which could help mitigate their growth, emissions would reach around 920 thousand tonnes in 2035 (+42% compared to 2005), as shown in Figure 2.2.

2.1.2 Carbon dioxide

Carbon dioxide is a result of the combustion of HCs and coal. Transportation accounts for a large share of carbon dioxide emissions. The transportation sector is clearly now the major contributor to carbon dioxide emissions. It should be noted that developing countries are rapidly increasing their transportation sector, and these countries represent a very large share of the world's population. The large amounts of carbon dioxide released into the atmosphere by human activities are believed to be largely responsible for the increase in the global temperature on Earth observed in recent decades. It is important to note that carbon dioxide is indeed digested by plants and sequestrated by oceans in the form of carbonates. However, these natural assimilation processes are limited and cannot assimilate all emitted carbon dioxide, resulting in an accumulation of carbon dioxide in the atmosphere.

Aircraft CO$_2$ emissions increased from 88 to 156 million tonnes (+77%) between 1990 and 2005 according to the data reported by EU28 and European Fair Trade Association (EFTA) Members States to the United Nations Framework Convention on Climate Change (UNFCCC). According to data from the IMPACT emissions model [25], CO2 emissions increased by 5% between 2005 and 2014. The increase in emissions is, however, less than the increase in passenger kilometers flown over the



For each traffic forecast, 'advanced' and 'low' technology improvements rates are applied to new aircraft deliveries from 2015 onwards. The upper bound of the range reflects the 'low' technology improvement rate, and the lower bound is the 'advanced' technology improvement rate.

Figure 2.3: Aircraft CO_2 emissions forecast [3, 25, 39]

same period (2005 to 2014). This was due to an improvement in fuel efficiency driven by the introduction of new aircraft, the removal of older aircraft, and improvements in operational practice. The average fuel burn per passenger kilometer flown for passenger aircraft, excluding business aviation, went down by 19% over this same period.

However, projections indicate that future technology improvements are unlikely to balance the effect of future traffic growth. Under the base traffic forecast and advanced technology improvement rate, CO2 emissions increases by 44% from 144 Mt in 2005 to 207 Mt in 2035, as can be seen from Figure 2.3.

2.1.3 Other Pollutants

Carbon monoxide and Unburned HCs result from the incomplete combustion of HCs. The first one results due to a lack of oxygen. It is a poison to human beings and animals that inhale/breathe it. Unburned HCs are also responsible for smog; the Sun's ultraviolet radiation interacts with the unburned HCs and NO in the atmosphere to form ozone and other products. Ozone is a molecule formed by three oxygen atoms. Also the impurities in fuels result in the emission of pollutants. The major impurity is sulfur, mostly found in diesel and jet fuel. The combustion of sulfur with oxygen releases sulfur oxides (SO_x).

Emissions of HC, CO and non-volatile PM have decreased between 2005 and 2014, while full-flight emissions of volatile PM have increased by 7%.

The total emissions of each of these pollutants are forecast to increase over the next twenty years, as can be seen in Table 2.1 from [24].

Table 2.1: Summary of emission indicators based on IMPACT data [24, 25].
(*below 3000 ft)

	Unit	Value		
		2005	2014	Base forecast 2035
				Advanced-Low Technology
			(% change vs. 2005)	(% change vs. 2005)
Average fuel burn	kg	0.0388	0.0314	0.0209 - 0.0222
(per passenger kilometer)			(-19%)	(-19%) - (-19%)
CO_2	Mt	144	151	207 - 219
			(+5%)	(+44%) - (+53%)
NO_X	1000 t	650	732	920 - 1049
			(+13%)	(+42%) - (+61%)
NO_X*	1000 t	53.3	58.8	73.3 - 83.1
			(+10%)	(+37%) - (+56%)
HC	1000 t	20.8	17.0	22.9
			(-18%)	(+10%)
HC*	1000 t	7.8	6.4	11.0
			(-18%)	(+40%)
CO	1000 t	143	133	206
			(-7%)	(+44%)
CO*	1000 t	52.4	48.2	85.5
			(-8%)	(+63%)

Table 2.2: Summary of noise indicators [24, 25]

	Unit	Value		
		2005	2014	Base forecast 2035
				Advanced-Low Technology
			(% change vs. 2005)	(% change vs. 2005)
45 STAPES airports				
L_{den} 55 dB area	km^2	2.251	2.181	1.983 - 1.587
			(-3%)	(-12%) - (+15%)
L_{night} 50 dB area	km^2	1.268	1.248	1.058 - 1.385
			(-2%)	(-17%) - (+9%)
L_{den} 55 dB population	millions	2.56	2.52	1.97 - 2.86
			(-2%)	(-23%) - (+12%)
L_{night} 50 dB population	millions	1.18	1.18	0.78 - 1.19
			(-1%)	(-34%) - (+1%)
EU28-EFTA airports				
Noise energy	10^{15} J	9.60	9.16	9.37 - 12.9
			(-5%)	(-2%) - (+34%)
Average noise energy	10^{18} J	7.29	6.41	4.14 - 5.70
(per operation)			(-12%)	(-43%) - (-22%)

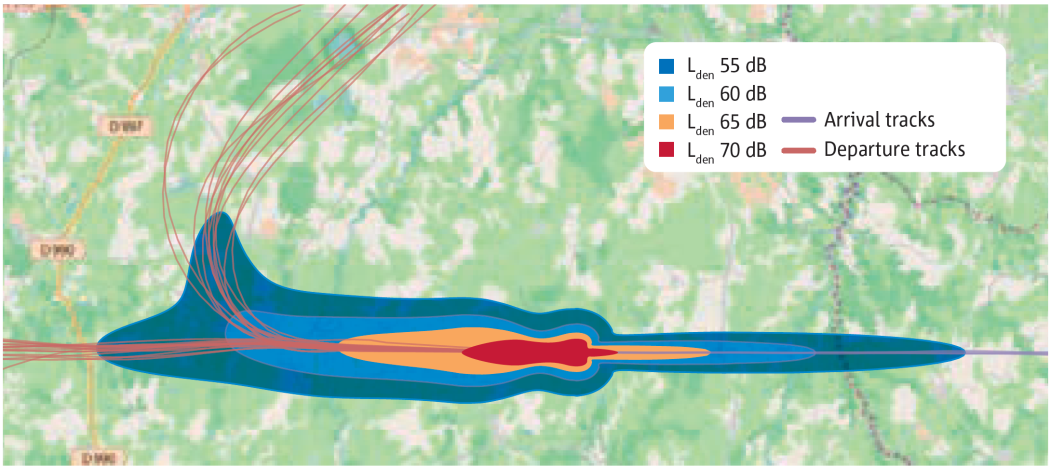


Figure 2.4: Example of notional airport noise contours [22]

2.2 Environmental impact of noise emissions

Aircraft noise exposure is typically assessed by looking at the area of noise contours around airports, as well as the number of people within these contours. A noise contour represents the area around an airport in which noise levels exceed a given decibel (dB) threshold. The noise metrics and thresholds presented are the L_{den}[1] 55 dB and L_{night}[2] 50 dB indicators, in line with what Member States are required to report under the EU Environmental Noise Directive (END). [4, 51] Total contour areas and populations were computed for 45 major European airports using the SysTem for AirPort noise Exposure Studies (STAPES) noise model. STAPES is a multi-airport noise model developed by EUROCONTROL. It is capable to provide valuable input for both European and international policy-making analyses, including, in particular, International Civil Aviation Organization (ICAO)'s Committee on Aviation Environmental Protection (CAEP).[26] These two metrics were complemented by noise energy[3], which was computed for all airports in the EU28 and EFTA region (about 2100 airports in 2014), as it is shown in Figure 2.4.

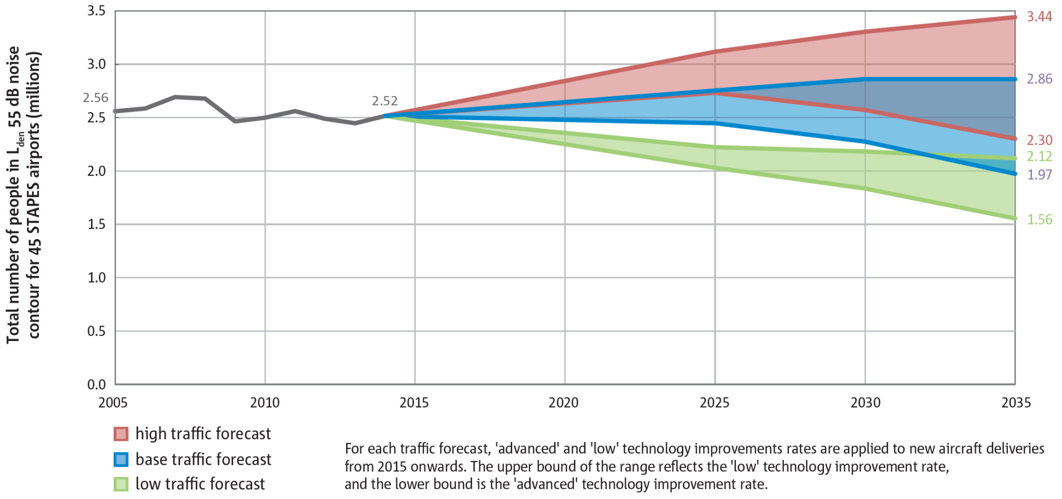
Noise exposure has stabilized over the past ten years. The total population inside the STAPES L_{den} and L_{night} contours decreased by only 2% (L_{den}) and 1% (L_{night}) between 2005 and 2014. A similar trend is observed for the total noise energy in the EU28 and EFTA region, which decreased by 5% during the same period. This overall noise reduction is due to technological improvements, fleet renewal, increased ATM efficiency and the 2008 economic downturn. Fleet renewal has led to a 12%

---

[1] L_{den} is defined as an equivalent sound pressure level averaged over a day, evening and night time period.[52, 51]

[2] L_{night} is defined as an equivalent sound pressure level averaged over a night time period.[52, 51]

[3] Noise energy is an indicator which combines the number of flights of aircraft with their respective certified noise levels. It is independent of how aircraft are operated at airports.



For each traffic forecast, 'advanced' and 'low' technology improvements rates are applied to new aircraft deliveries from 2015 onwards. The upper bound of the range reflects the 'low' technology improvement rate, and the lower bound is the 'advanced' technology improvement rate.

Figure 2.5: Noise emissions forecast [25]

reduction in the average noise energy per operation between 2005 and 2014.

Under the base (most likely) traffic forecast, a continued 0.1 dB reduction per annum for new aircraft deliveries (low technology improvement rate) could halt the growth of the overall noise exposure in the 2035 timeframe, while a 0.3 dB reduction per annum (advanced technology improvement rate) could lead to a net reduction of the exposure compared to 2014 even under the high traffic forecast, as it can be seen in Figure 2.5 and Table 2.2 from [24].

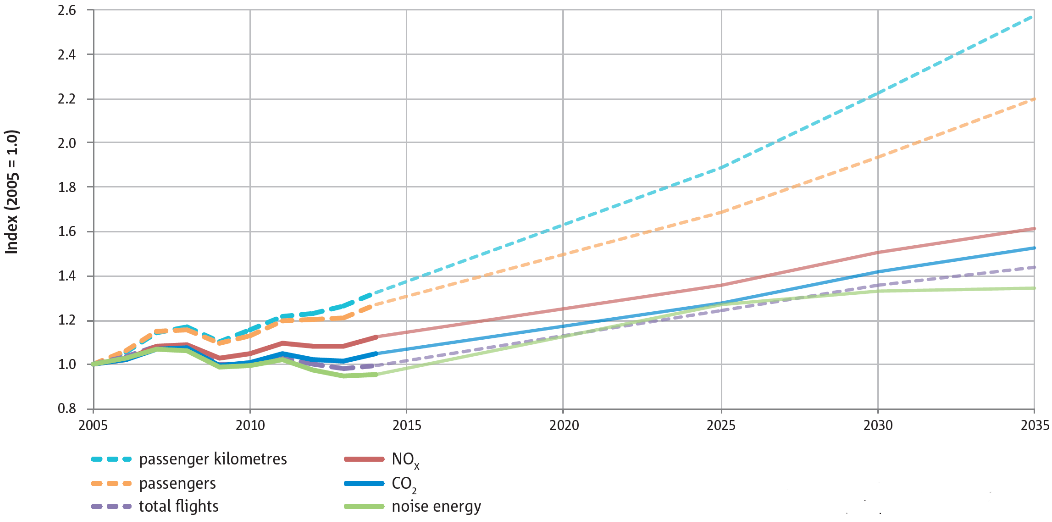


Figure 2.6: Noise emissions and pollutants emissions forecast 2005-2035. Forecast years are for the base (most likely) traffic and low technology improvement scenarios [25]

2.3 Hybrid-Electric aircraft

Conventional vehicles with Internal Combustion Engine (ICE) provide good performance and a long operating range by utilizing the high-energy-density advantages of petroleum fuels. However, conventional ICE vehicles have the disadvantages of poor fuel economy and environmental pollution. Battery Electric Vehicles (BEV), on the other hand, possess some advantages over conventional ICE vehicles, such as high energy efficiency and zero environmental pollution. But the performance, especially the operation range per battery charge, is far less competitive than for ICE vehicles due to the much lower energy density of the batteries than that of gasoline. Hybrid-Electric Vehicles (HEV), which use two power sources (a primary power source and a secondary power source), have the advantages of both ICE vehicles and EVs and overcome their disadvantages.

Hybrid-Electric Aircraft (HEA) are being seriously considered as one of revolutionary design concepts. Such aircraft require a significant increase in on-board power generation capability, from 1.5 MW on a current state-of-the-art more-electric aircraft (i.e. the Boeing 787), to 25 MW upwards for a hybrid electric aircraft. This requires significant development both in the design of appropriate aero-electrical power systems and in the development of appropriate technologies to enable these aero-electrical power systems to be realized within the proposed 25-year time frame.

HEA have gas turbine engines which drive electrical generators to power electrically motor driven fans. Depending on the variant of hybrid-electric aircraft being considered, thrust may be provided via a combination of gas turbines and electrical

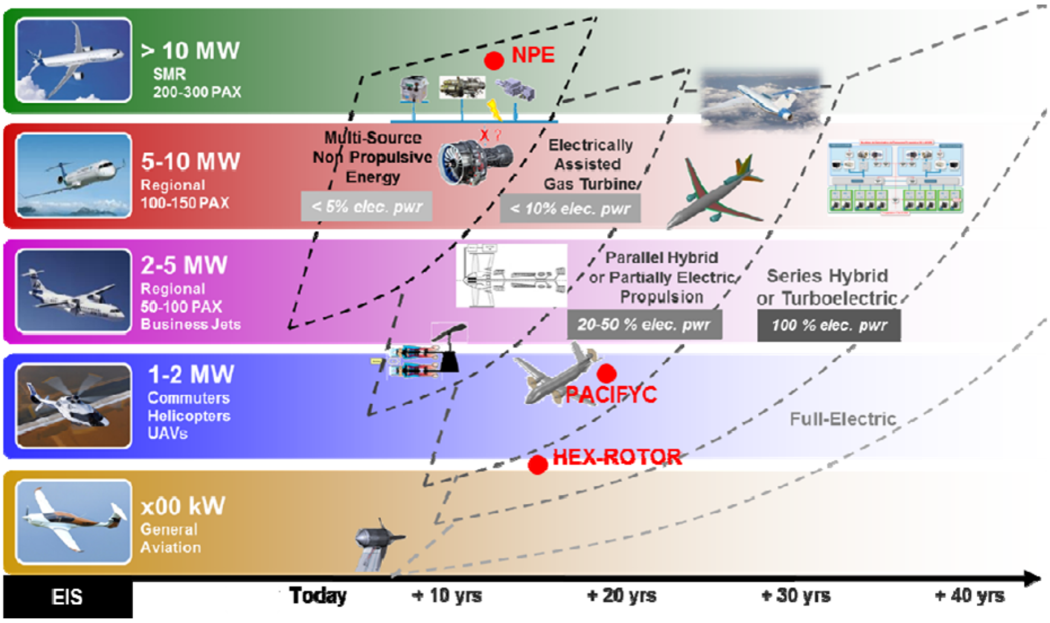


Figure 2.7: Hybrid-Electric trend over the next 40 years [41]

propulsors, or only via the electrical propulsors. This design philosophy is not new, and in fact is commonly found throughout the industry in rail, marine and electric vehicles. Within these sectors, electrical propulsion has been shown to have a number of benefits, including:

- improved efficiency, particularly at part load;
- use of excess power generation for power supply to auxiliary loads such as pumps or pressurization systems;
- greater flexibility in the location of electrical loads;
- reduced volume of machinery;
- reduced vibration and noise.

In principle, the overall structure of a HEA could be similar to conventional ones, with gas turbine engines used for electrical power generation for driving electrical propellers.

One of the most significant benefits associated with hybrid electric aircraft is the flexibility in configuration and operation. For example, the electric propulsion can be used continuously throughout flight or for specific sections of the flight plan where the power demand is higher. Furthermore, there is the possibility to integrate appropriate energy storage systems alongside the gas turbine driven generators in order to fully optimize system performance. So against continuous increasing of energy demand and rising fuel price, hybrid-electric propulsion systems have the potential to reduce fuel consumption in the aviation industry, particularly in the lighter sectors. A saving up to 20% for a typical transfer mission and up to 30% for a training mission is stated to be possible in [32] for a light aircraft. According to [29], a 20% fuel reduction[4] is achievable by 2030 for a commuter aircraft, while a 15% reduction is expected for a narrow body liner.

The largest reduction in fuel burn is expected by using the available electric energy during the cruise, since usually, it is the longest flight phase. The potential in block fuel reduction diminishes with increasing design range. The fuel burned during take-off represents only a few percents of the block fuel. Therefore, only a small impact on fuel burn can be expected using the electric motor during the take-off. However, using the electric motor would have a significant benefit on the gas-turbine performance and it would help to increase the life cycle of the combustion engine. In addition, electric taxiing and its potential benefit make the electric propulsion appealing. [57]

---

[4] Value for the 85-percentile mission length, actual value goes from 10% to 39% depending on the mission range.

However, significant challenges do exist for the realization of hybrid electric aircraft given the significant upscaling of electrical generation and distribution onboard. The efficiency of aircraft is far more sensitive to weight than other applications where hybrid technologies have been employed. Traditionally electric components struggle to match the power density of their mechanical equivalents (particularly at higher power levels) and therefore any potential the weight penalty which comes with the addition of electrical components must be offset by the resulting gains in efficiency and reductions in noise in future hybrid electric designs.

Currently, there are different examples of firms teaming up to realize a hybrid-electric or pure electric aircraft.

2.3.1 Products, prototypes and concepts

At least 17 manned hybrid-electric and full-electric fixed-wing aircraft have flown, three of which are commercially available products. Two more technology demonstrators are reasonably expected to fly by 2020. There are also numerous industry and government funded advanced concept studies focused on higher technology and power levels. This section reviews most of the flight-tested electric aircraft and the well-developed studies. Table 2.3 lists noteworthy manned electric aircraft with first-flight dates since 2000. Table 2.4 lists major design studies by government, established industry firms, and start-ups. Different propulsion architectures are considered: Full Electric (FE), Parallel Hybrid Electric (PHE), Series Hybrid Electric (SHE), Turbo Electric (TE) and Fuel Cell (FC).

2.4 Models for cost estimation

The estimation of the cost of developing an aircraft is an essential part of the design process. The Development And Procurement Costs of Aircraft (DAPCA) is a method used to estimate the development cost of new military aircraft. It is developed by the RAND Corporation and it is the most used model in the preliminary phase of aircraft design. The DAPCA is the latest study of cost estimating relationships for new military aircraft turbine engine development and production programs. The method, which is commonly referred to as DAPCA-IV, establishes special cost estimating relationships (CERs), which are a set of statistical equations that predict aircraft acquisition costs using only basic information like empty weight and maximum airspeed. The DAPCA-IV can be used to estimate cost for research, development, testing, and evaluation (RDT&E) and even allows workforce estimation to take place. In short, the CERs estimate separately the cost of engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, and quality control as well as the total program cost. The estimating relationships, expressed in the form of exponential equations, were derived by multiple least-squares regression analysis. They were derived from a database consisting of 34 military aircraft with first flight dates ranging from 1948 to 1978. The aircraft technical data were obtained for the most part from either original engineering documents such as manufacturer's performance substitution reports or from official US Air Force and US Navy documents. The cost data were obtained from the airframe manufacturers either directly from their records or indirectly through standard Department of Defense reports such as the contractor costs data reporting system. Consequently, the model is highly based toward the price structure adapted by the Pentagon, which does not apply to the general aviation aircraft industry. This can be seen in the grossly overestimated development costs for GA aircraft predicted using the unmodified DAPCA-IV method.

In 2000, Professor Emeritus Charles Eastlake of Embry-Riddle Aeronautical University and later in 2014 Professor Snorri Gudmundsson have adapted the original DAPCA-IV formulation to GA and executive jet aircraft to better reflect the development and operational cost of such airplanes. The first phase of modification was an intuitive adjustment based upon personal experience with the differences between designing military and civilian aircraft. Then the second phase of adjustment was made to tune the model to predict the correct current price of a GA aircraft and a business aircraft.

Another effort is needed in order to adapt this model and its equations to the case under analysis. This effort will be explained in detail in Chapter 4.

Table 2.3: Summary of flyable manned hybrid and electric aircraft [8].
(*commercially available)

Name	First flight	Arch.	Seats	TOGW [kg]	Max power [kW]	e_b [Wh/kg]	Range/ Endurance [nmi]	Ref
Lange Antares 20E *	2003	FE	1	660	42	136		[29]
Fishman Electraflyer C	2008	FE	1	283	13.5	-	90 min	[19]
Boeing HK-36 FCD	2008	FC	1	860	75	NA	45 min	[48]
Yuneec E430	2009	FE	2	470	40	154		[59]
Siemens/ Diamond E-Star	2011	SHE	2	800	70	-		[5]
Pipistrel Taurus Electro G2 *	2011	FE	2	450	40	-		[55]
Pipistrel Taurus Electro G4	2011	FE	4	1500	150	180	244	[47]
IFB Stuttgart eGenius	2011	FE	2	950	60	204	244	[47]
Embry-Riddle Eco-Eagle	2011	PHE	2	1075	105	125	170	[49]
Fishman Electraflyer *	2012	FE	1	238	15	-	120 min	[19]
Chip Yates Long ESA	2012	FE	1	680	192	-		[8]
Siemens/ Diamond E-Star2	2013	SHE	2	800	80	-		[20]
Airbus E-Fan	2014	FE	2	600	60	207	60 min	[33]
Cambridge SOUL	2014	PHE	1	235	20	144		[31]
Pipistrel Alpha Electro *	2015	FE	2	550	60	171	70	[54, 56]
Airbus E-Fan 1.2	2016	SHE	2	600	60	-		[33]
Siemens Extra 300 (330LE)	2017	FE	1	1000	260	-		[2]

Table 2.4: Summary of electric fixed-wing aircraft concepts and studies [8].
(*tailcone propulsor power only, **includes electric motor only)

Name	Target EIS	Arch.	Seats	TOGW [kg]	Max power [MW]	e_b [Wh/kg]	Range [nmi]	Ref
NASA X-57 "Maxwell"	2018	FE	2	1360	0.144	130		[10]
Eviation Alice	2019	FE	11	6350	0.780	260	560	[28]
Ampaire Tailwind	2020s	FE/SHE					350	[8]
Zunum	2020s	SHE	12	5216	1		700	[1]
XTI Tri-Fan 600	2024	SHE	6	2404	1.5		1200	[18]
NASA STARC-ABL	2035	TE	154	60000	2.6(*)		3500	[71]
Boeing SUGAR Volt	2035	PHE	154	68040	1.0(**)	750	3500	[7]
Bauhaus Luftfahrt Ce-Liner	2035	FE	189	109300	33.5	2000	900	[40]
Airbus VoltAir	2035	FE	~33	~33000		750+	~900	[66]
ESAero/Wright ECO-150R	2035	TE	150	60-75k	12.7		1650	[63]
NASA N3-X	2045	TE	300	227000	50		7500	[30, 42]
Airbus/R-R E-Thrust	2050	SHE	90		9.0	1000		[34]

Chapter 3

Market Analysis

This chapter tries to answer the question “What is the total volume of hybrid-electric micro-feeder aircraft that would be purchased by a group of buyers in a specific geographic area?”. Our market analysis focuses firstly at the prospectively interested geographic areas interested and secondly at the estimation of the potential users.

Predicting the demand for a hybrid-electric micro-feeder service is challenging, given the novelty of this mode of transportation. This limits the potential of using historical data, as the past market conditions are quite distinct from a future hybrid-electric micro-feeder market. It is important to understand that, in practice, it is difficult if not impossible to observe the actual demand for a flight, even for conventional aircraft. The notion of *total demand* for a particular flight or set of flights operated over a period of time is, therefore, a theoretical concept. Thus, the analysis of total demand requires models and assumptions. However, it is primarily important to define the term *demand*. *Demand* is the total number of potential passengers that might make a reservation on a particular scheduled flight leg. In line with our definition of demand for an origin-destination market in air transportation economics, the demand for a flight leg reflects a maximum potential, independent of the capacity being offered on the flight.

For this reason, the market analysis follows three steps. The first step is presented in Section 3.1. Each country’s transportation system is analyzed. It starts from an analysis of all the data available in EUROSTAT related to the ground transportation and then they are combined into one single index. This index represents the "ground transportation system efficiency". The second step reported in Section 3.2 exploits the trans-European transport network defined by EU to identify the main European airports and all the data related to them. This helps to define two different clusters: minor airports and major airports. The third step defines all the candidate routes for the micro-feeder service through an adequate procedure shown in Section 3.3. Section 3.4 shows a procedure to evaluate the potential volume of the users of a micro-feeder service under different hypothesis.

Since the amount of computing power to calculate the potential market is very high, this is done only for three case studies. The above procedure is developed in order to have the possibility to expand the volume of users of the three case studies to all the similar countries.

3.1 European transportation data analysis

The purpose of this first part of the study is to obtain useful data to understand better how the aircraft can fit into the panorama of European passenger transport, for each country. In particular, it presents recent data on the inland transport network of the EU, EFTA and candidate countries. The evolution of the transport network is closely linked to the general development of the economy. This type of analysis allows finding where a micro-feeder service can be more competitive.

- Road transport:
  - infrastructure: motorways and e-roads length;
  - vehicles: number of passenger cars and motorcycles;
  - traffic: annual movements on traffic territory by car and motorcycles.
- Railway transport:
  - infrastructure: railway track length;
  - vehicles: number of passenger railway vehicles and their capacity;
  - traffic: passenger trains annual movements and total annual passenger. transport
- Air transport:
  - infrastructure: number of commercial airports;
  - traffic: annual air passenger transport.

The EU has one of the densest transport networks in the world. This reflects a number of factors, including population density and transport demand. Transport demand is especially high in urban, industrial and other densely populated areas.

The output of this first step is a sort of "transport efficiency" for each country. This is an indicator which can identify how the considered country is efficient with respect to Europe for each transport mode.

Note that the air transport statistic will be considered in Section 3.2 and Section 3.3.

3.1.1 Motorways

Comparing the length of the motorways to the area of the regions gives a good picture of the motorway infrastructure and concentration within the EU.

The motorway network is especially dense in regions with urbanized areas. The most significant motorway expansion between 2007 and 2016 took place in regions of Spain, Ireland, France, Hungary and Romania. This reflects the general development programs of the motorway network in these countries over the last decade. These impressive growth rates are explained by the very limited motorway networks in these regions in the 2000s.

The highest motorway densities are obviously found around European capitals and other big cities, in large industrial conurbations and around major seaports. Most European capitals and large cities are surrounded by a ring of motorways in order to meet the high demand for road transport originating from these metropolitan areas. Dense motorway networks can be found around capitals: Wien (104 m/km^2), Madrid (96 m/km^2), Praha (89 m/km^2), Berlin (86 m/km^2), and Amsterdam (Noord-Holland: 72 m/km^2). Since the motorways are generally concentrated in a ring close to the cities, the motorway density decreases when the area of the Nomenclature of Territorial Units for Statistics (NUTS)2[1] region concerned increases. As a result, the motorway density reported for the small NUTS2 region of Wien is higher than for the much larger NUTS2 region of Île-de-France, even though the motorway network of Paris is larger.

Other densely populated regions with high motorway density include the Randstad region in the western part of the Netherlands (Utrecht: 121 m/km^2, Zuid-Holland: 108 m/km^2, and Noord-Holland: 72 m/km^2).

High motorway densities are also found around the major seaports of northern Europe: the motorway densities of the NUTS2 regions of Bremen (191 m/km^2) with the port of Bremerhaven, of Zuid-Holland with the port of Rotterdam (108 m/km^2) and of Hamburg (107 m/km^2) are among the highest of all European regions.

Another reason for the high density of the motorway network in some central European countries (such as Germany) is the proportionately high volume of transit freight traffic.

The density of motorways on islands is generally low, as islands cannot be reached directly by road: instead, they rely on sea or air transport.

---

[1] NUTS is a geocode standard for referencing the subdivisions of countries for statistical purposes. The standard is developed and regulated by the European Union, and thus only covers the member states of the EU in detail. From the NUTS Regulation, the average population size of the regions in the respective level shall lie within the following thresholds: NUTS1 3-7 mln, NUTS2 0,8-3 mln, NUTS3 150-800 k. NUTS0 collect all the 28 Member States.

Table 3.1: Motorway network length and density per country [15, 16]

Country	Area [km^2]	Motorway length network [km]	Motorway network density [m/km^2]
Austria	83,855	1,719	20.50
Belgium	30,528	1,763	57.75
Bulgaria	110,994	740	6.67
Croatia	56,594	1,310	23.15
Czech Republic	78,866	1,223	15.50
Denmark	43,075	1,255	29.14
Estonia	45,227	145	3.21
Finland	338,424	890	2.63
France	632,833	11,612	18.35
Germany	357,021	12,996	36.40
Greece	131,990	670	5.08
Hungary	93,030	1,924	20.68
Ireland	70,273	916	13.03
Italy	301,338	6,943	23.04
Latvia	64,589	75	1.16
Lithuania	65,200	314	4.82
Luxembourg	2,586	161	62.26
Malta	316	-	-
Netherlands	41,543	2,756	66.34
Norway	385,248	392	1.02
Poland	312,685	1,640	5.24
Portugal	92,390	3,065	33.17
Romania	238,391	747	3.13
Slovakia	49,035	463	9.45
Slovenia	20,273	773	38.13
Spain	504,030	15,444	30.64
Sweden	449,964	2,118	4.71
Switzerland	41,285	1,447	35.05
United Kingdom	243,610	3,764	15.45

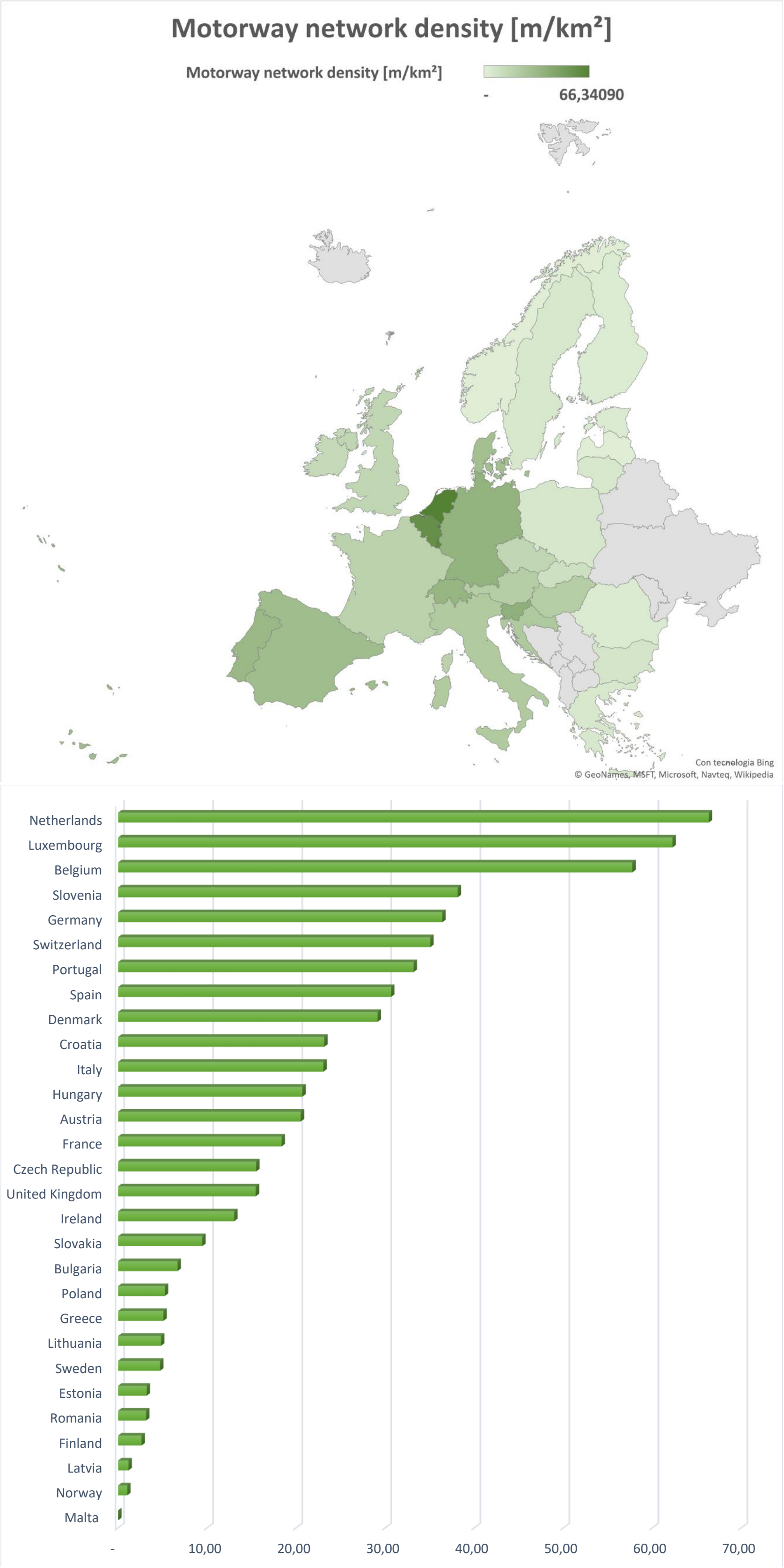


Figure 3.1: Motorway network density per country [16]

3.1.2 Railways

In general, the density of railway lines is high in western and central parts of Europe and lower in the peripheral areas. The highest network densities can be found in the regions of Switzerland, the Czech Republic and Belgium (all above 120 m/km^2), followed by the regions of Germany and Luxembourg (all above 100 m/km^2).

Looking at individual regions, the densest railway networks are observed in capital regions: Berlin (720 m/km^2) and Praha (475 m/km^2).

While central European capitals have traditionally had a strong railway infrastructure, the strikingly high values are to a large extent due to the small size of these regions within the NUTS2 classification. Furthermore, the density of urban infrastructure tends to be much higher than the density of interurban roads and railway lines. Other capital regions with relatively dense rail networks are Bucharest (Bucuresti — Ilfov: 153 m/km^2), Paris (Île-de-France: 152 m/km^2) and Amsterdam (Noord-Holland: 89 m/km^2).

Freight transport railway lines also play a leading role in several regions where coal and steel industries remain predominant, such as the Saarland region in western Germany (136 m/km^2) and Ślaskie in south-west Poland (159 m/km^2).

Focusing on railway infrastructure at the country level, there are significant differences among countries with respect to the share of the network that is electrified. Luxembourg (95%), the Netherlands: (76%) and Sweden (75%) registered the highest shares, while Ireland and the Baltic States were the only countries where less than 20% of the network is electrified.

3.1.3 Data analysis

EUROSTAT collects regional statistics on the infrastructure of road, railways and inland waterways, as well as vehicle stocks and road accidents. The data are provided by the Member States and some EFTA countries. The data are collected at NUTS0, NUTS1 and NUTS2 levels for these transport indicators. For the purpose of this work only the statistics related to the road and railways are considered. Figure 3.1 shows motorway network density data collected and mapped at NUTS0, as well as railway network density in Figure 3.2.

Table 3.3 and Table 3.1 reports area and network lengths per country. The comparison of these data gives a network density which is a good picture of the infrastructures efficiency.

It has been decided to combine the railway and the motorway density together. It comes out an index representing the “ground transportation system efficiency” of each country. This indicator has been called *ground transportation network density* and it is reported in Table 3.4 and mapped in Figure 3.3. This index helps to

Table 3.2: Ground transportation network density classification

High ground transportation density	Medium ground transportation density	Low ground transportation density
Belgium, Luxembourg, Switzerland, Germany, Netherlands, Czech Republic	Hungary, Slovenia, United Kingdom, Slovakia, Poland, Spain, Denmark, Austria, Italy Croatia, France, Portugal	Romania, Ireland, Latvia, Estonia, Finland, Norway Bulgaria, Lithuania, Sweden, Greece, Malta

underline the strength or the weakness of the ground transportation of each country. In this way, it is immediate to see where our service will be used as an optional mode to travel, with respect to the existing modes, just for convenience, and where it will be used as a primary mode of transportation due to a lack of an alternative. The ground transportation density defines a ranking of countries. Belgium, Luxembourg, Switzerland, Germany, the Netherlands and Czech Republic head the list. Here the transportation density is the highest in Europe and they can be considered to have the best ground transportation links with respect to their size. Here, the ground transportation network covers entirely the country. On the opposite side, there are Romania, Bulgaria, Ireland, Lithuania, Latvia, Sweden, Estonia, Greece, Finland, Norway, and Malta. For more reasons, in these countries, the ground transportation suffers from weak transportation capacities and weak coverage. Among the various reasons, the territorial aspect plays a relevant role, for example the case of Greece for its number of islands or Malta for the small size of the country, as well as for the huge size of the Scandinavian peninsula. Between these two groups, there are those countries with an average ground transportation network. Here, the transport network covers just partially the country.

The three above clusters defined by the density indicator will be used in Section 3.5 allowing to identify three representative case studies, one for each cluster. The skip from a cluster to the following is established where a significant difference between two neighboring values exists.

Table 3.3: Railway network length and density per country [15, 16]

Country	Area [km^2]	Railway length network [km]	Railway network density [m/km^2]
Austria	83,855	5,491	65.48
Belgium	30,528	3,578	117.20
Bulgaria	110,994	4,029	36.30
Croatia	56,594	2,604	46.01
Czech Republic	78,866	9,564	121.27
Denmark	43,075	3,181	73.85
Estonia	45,227	1,161	25.67
Finland	338,424	5,926	17.51
France	632,833	28,364	44.82
Germany	357,021	38,466	107.74
Greece	131,990	2,240	16.97
Hungary	93,030	7,811	83.96
Ireland	70,273	1,931	27.48
Italy	301,338	16,788	55.71
Latvia	64,589	1,860	28.79
Lithuania	65,200	1,911	29.31
Luxembourg	2,586	275	106.34
Malta	316	-	-
Netherlands	41,543	3,058	73.61
Norway	385,248	3,895	10.11
Poland	312,685	19,132	61.19
Portugal	92,390	2,546	27.56
Romania	238,391	10,774	45.19
Slovakia	49,035	3,206	65.38
Slovenia	20,273	1,209	59.64
Spain	504,030	16,167	32.08
Sweden	449,964	10,882	24.18
Switzerland	41,285	5,196	125.86
United Kingdom	243,610	16,253	66.72

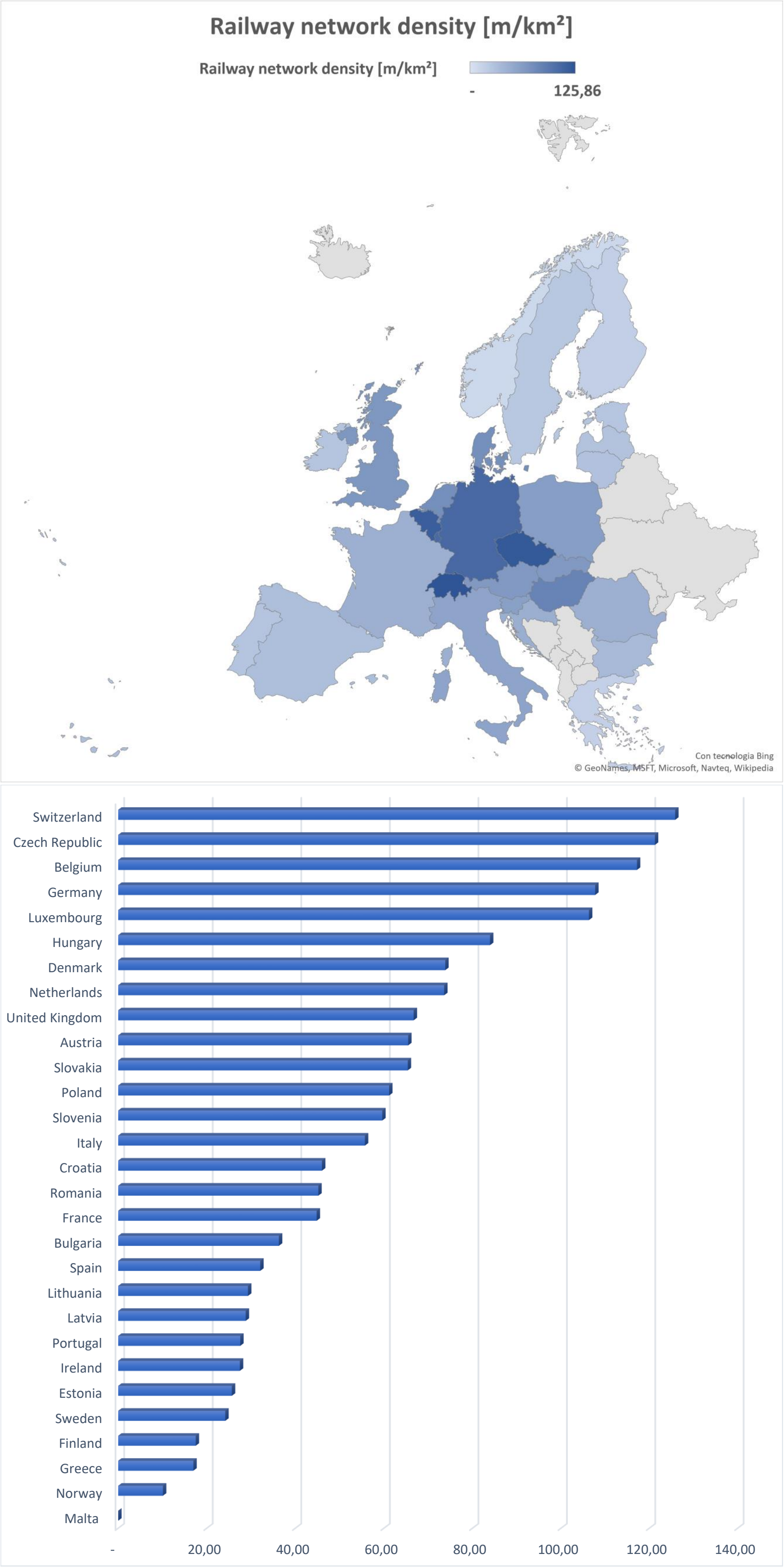


Figure 3.2: Railway network density per country [15]

Table 3.4: Ground transportation network density per country

Country	Ground transportation network density [m/km^2]
Austria	87.98
Belgium	174.95
Bulgaria	42.97
Croatia	69.16
Czech Republic	136.77
Denmark	102.98
Estonia	28.88
Finland	20.14
France	65.17
Germany	144.14
Greece	22.05
Hungary	104.64
Ireland	40.51
Italy	78.75
Latvia	29.95
Lithuania	34.13
Luxembourg	168.60
Malta	-
Netherlands	139.95
Norway	11.13
Poland	68.43
Portugal	62.73
Romania	43.33
Slovakia	74.83
Slovenia	97.77
Spain	64.72
Sweden	28.89
Switzerland	160.91
United Kingdom	82.17

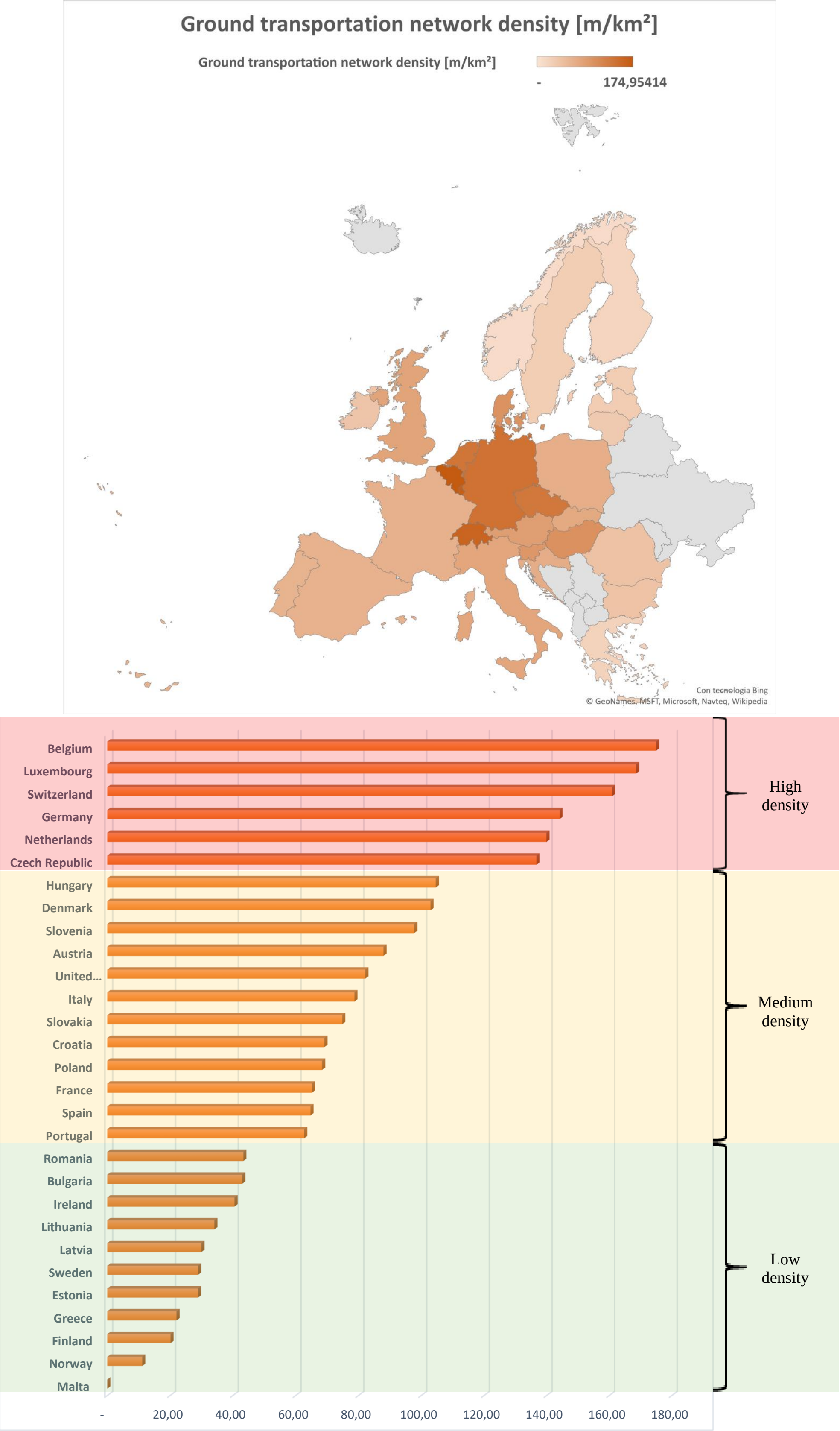


Figure 3.3: Ground transportation network density per country [15, 16]

3.2 Identification of the main nodes

The second step is to analyze the European transport network in order to identify the main nodes for each country. So, it is crucial to consider the Trans-European Transport Network TEN-T [60], which already defines methods and criteria to identify the main nodes for each transportation mode all over Europe. The effort requested by the author in this phase is to extract only the data of airports belonging to the network and to classify them in minor airports and major airports.

3.2.1 Trans-European Transport Network TEN-T

The Trans-European Transport Network (TEN-T) is a network which comprises roads, railway lines, inland waterways, inland and maritime ports, airports and rail-road terminals throughout the 28 Member States. This characteristic is a key factor for the network's efficient, safe and secure operation, using seamless transport chains for passengers and freight. It builds on existing and planned infrastructure in these States which has been identified on the basis of a single methodology and which has to comply with common requirements and standards set out by EU.

In the past, European transport systems developed mostly according to national criteria, with the consequent scarcity or complete absence of interconnections at the borders or along strategic corridors. The weakness of transport interconnections hinders economic growth.

The methodology features a dual layer network structure:

- comprehensive network;
- core network.

Full respect of relevant EU legislation has to be ensured when the methodology is applied. The methodology consists of a number of criteria which are consistently applied. In a first step, the comprehensive network is identified. In a second step, parts of the comprehensive network are identified as the core network.

The network has different targets, some of which can be satisfied optimally by a hybrid-electric micro-feeder. It must:

- ensure the sustainable mobility of persons and goods within an area without internal frontiers under the best possible social and safety conditions, while helping to achieve the Community's objectives, particularly in regard to the environment and competition, and contribute to strengthening economic and social cohesion:
- offer users high-quality infrastructure on acceptable economic terms;

- include all modes of transport, taking account of their comparative advantages;
- allow the optimal use of existing capacities;
- be, insofar as possible, inter-operable within modes of transport and encourage inter-modality between the different modes of transport;
- be, insofar as possible, economically viable;
- cover the whole territory of the Member States so as to facilitate access in general, link island, landlocked and peripheral regions to the central regions and interlink without bottlenecks the major conurbations and regions of the Community;
- be capable of being connected to the networks of the EFTA States, the countries of Central and Eastern Europe and the Mediterranean countries, while at the same time promoting interoperability and access to these networks, insofar as this proves to be in the Community's interest.

For the purpose of this work, only the Trans-European Airport Network is considered. According to Article 13 of the Decision No 1692/96/EC [50] of the European Parliament and of the Council of 23 July 1996 on Community guidelines for the development of the trans-European transport network, the Trans-European Airport network comprises airports opened to commercial air traffic and situated within the territory of the Community.

These airports shall be classified differently according to the volume and type of traffic they handle and according to their function within the network. They shall permit the development of air links and the interconnection of air transport and other modes of transport.

The international connecting points and the Community connecting points constitute the core of the trans-European airport network. Links between the Community and the rest of the world shall be mainly via the international connecting points. The Community connecting points essentially provide links within the continent, with extra-Community services still accounting for a small proportion of their business.

Regional connecting points and accessibility points constitute the comprehensive nodes of the network shall facilitate access to the core of the network or help to open up peripheral and isolated regions.

International and Community connecting points have been gradually linking to the high-speed lines of the rail network, where appropriate. The network shall include the infrastructures and the facilities which permit the integration of air and rail transport services.

In project MAHEPA the same node classification is done with a different terminology. The major hubs represent the international and Community connecting points, while the minor airports are the second class defined by EU, the regional connecting points.

In the present state of knowledge, aerodromes are not considered in the TEN-T and they will hardly be in the near future. For this reason, aerodromes are not considered in the analysis but the built model for evaluating the market implementation of future hybrid-electric can be easily extended to them. Considering aerodromes as part of a modified comprehensive network or as a sub-network which aim is to facilitate access to the comprehensive nodes of the network. Note that, the aircraft must comply with the regulatory restrictions having to operate on minor airports.

Today, the extension to aerodrome is possible if applied on a micro-feeder intended as a small commuter aircraft. The current regulation allows the operations on aerodromes by aircraft with a maximum certificated takeoff weight of 5670 kg or less and a seating configuration, excluding the pilot seat(s), of nine or fewer. [21]

3.2.2 The comprehensive network

The comprehensive network is a multi-modal network of relatively high density which provides all European regions (including peripheral and outermost regions) with an accessibility that supports their further economic, social and territorial development as well as the mobility of their citizens. Its planning has been based on a number of common criteria.

The comprehensive airport network, essentially, results from updating and adjusting the current TEN-T, as defined in [50].

Updating and adjustment abided by a number of principles as a result of the methodology used:

- eliminate dead ends and isolated links in the current TEN-T if not justified by geographical particularities, either by removing such links or by extending them to close network meshes;
- revise the selection of airports which are open to commercial traffic, according to at least one of the following specific criteria:
    - passengers: Airports with an annual traffic volume exceeding 1‰ of the total annual EU air passenger traffic. This annual traffic volume represents the average of the latest three-years totals for which data are available from EUROSTAT;
    - freight: Airports with an annual traffic volume exceeding 2‰ of the corresponding total annual cargo handled in EU airports. This annual

traffic volume represents the average of the latest three-years totals for which EUROSTAT data are available;

  - airports located on islands;
  - airports located in peripheral or landlocked areas provided their distance from another TEN-T airport is at least 100 km or, in case they are connected to a high-speed railway line, at least 200 km.

3.2.3 The core network

The core network is a subset of the comprehensive network, it represents the strategically most important nodes and links of the trans-European transport network. Therefore, only elements of the comprehensive network are selected for the core network. The core network is identified in the two following steps:

1. identification of the main nodes of the Core Network;
2. identifying the links between the primary main nodes.

As already said, the main nodes are those of the highest strategic importance for EU. They can be identified with respect to the volume of passengers and/or freight.

Multi-modal links are selected from the comprehensive network to connect the primary main nodes, following the corresponding (potential) main traffic flows.

The following paragraph set out the criteria [12] to identify the nodes of the core network:

- the capital city of each Member State and cities with EU capital function;
- every Metropolitan European Growth Area (MEGA) defined by European Spatial Planning Observatory Network (EPSON);
- the main city of an island or a group of islands forming a NUTS 1 region with at least 1 million inhabitants;
- one main border crossing point per mode between each EU Member State with external border and each of its neighboring non EU Member States which is the one with the highest long-distance traffic flow. This does not apply to Norway and Switzerland, for which special agreements exist. Border crossing points only serve as auxiliary points for network planning, but do not provide any other core node function;
- airports with an annual passenger volume of min. 1% of the corresponding EU total.

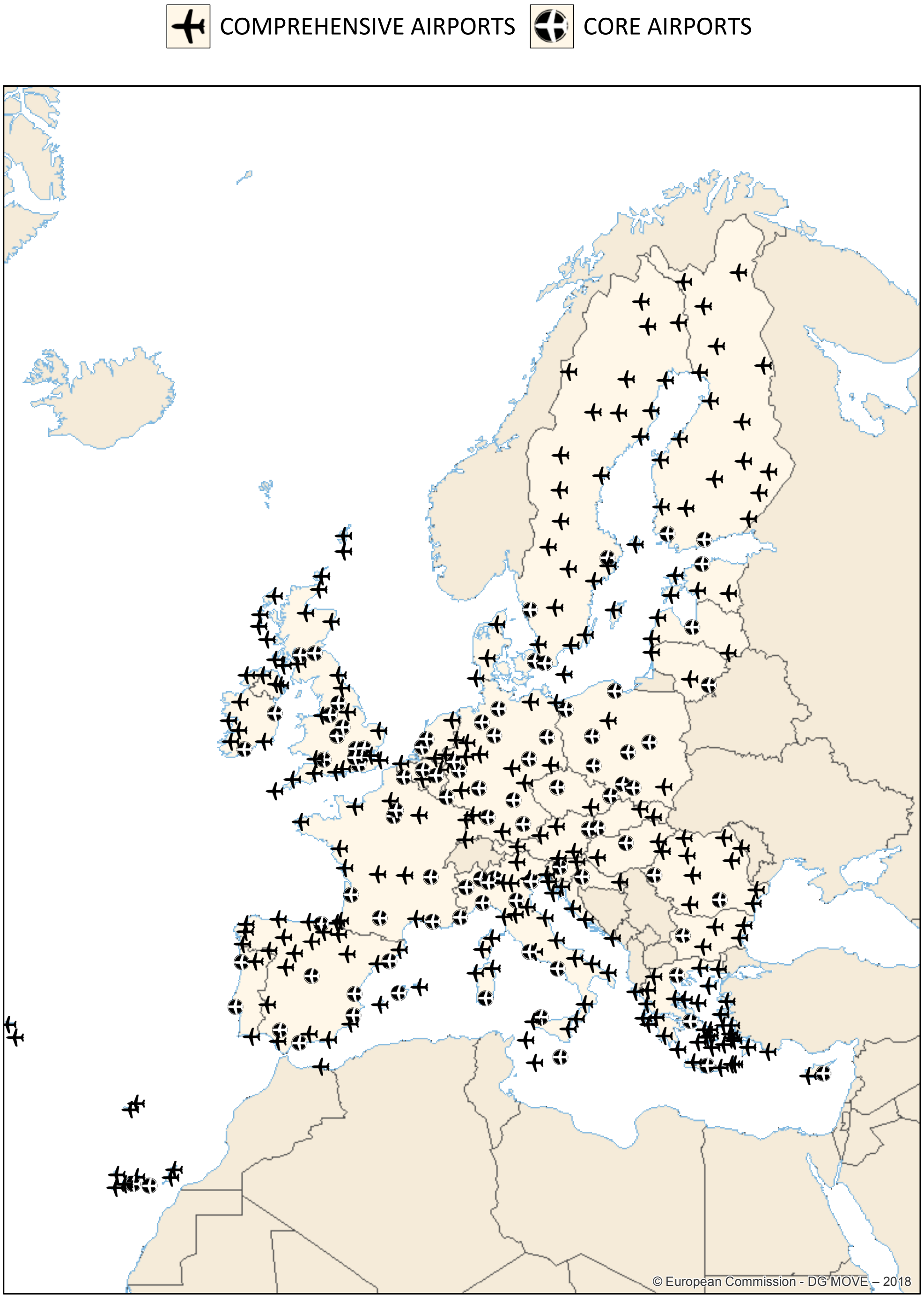


Figure 3.4: TEN-T core and comprehensive airports map [17]

Table 3.5: List of the major airports (core network) [13]

Member State	Major airports
Belgium	Bruxelles, Liège
Bulgaria	Sofia
Czech	Republic Ostrava, Praha Ruzyne
Denmark	Kobenhavn Kastrup, Aarhus
Germany	Berlin Schönefeld, Bielefeld, Bremen, Düsseldorf, Frankfurt Main, Hamburg, Hannover, Köln Bonn, Leipzig, Mannheim, München, Nürnberg, Stuttgart
Estonia	Tallinn
Ireland	Cork, Dublin
Greece	Athens, Iraklion, Thessaloniki Makedonia
Spain	Alicante, Barcelona, Bilbao, Las Palmas, Madrid Barajas, Málaga, Palma de Mallorca, Sevilla, Tenerife Reina, Valencia
France	Bordeaux Merignac, Lille Lesquin, Lyon St.Exupéry, Marseille, Provence, Nice Côte d'Azur, Paris Charles de Gaulle, Paris Orly, Toulouse Blagnac
Croatia	Zagreb
Italy	Bologna, Cagliari, Genova, Milano Linate, Milano Malpensa, Bergamo Orio al Serio, Napoli Capodichino, Palermo, Roma Fiumicino, Torino, Venezia
Cyprus	Larnaka
Latvia	Riga
Lithuania	Vilnius
Luxembourg	Luxembourg
Hungary	Budapest Liszt Ferenc
Malta	Valletta Malta Luqa
Netherlands	Amsterdam Schiphol, Rotterdam
Austria	Wien Schwechat
Poland	Gdánsk Gdynia, Katowice Pyrzowice, Kraków, Lodz, Poznan, Szczecin Swinoujscie, Warszawa, Wroclaw
Portugal	Lisboa, Porto Sa Carneiro
Romania	Bucuresti Henri Coanda, Timisoara
Slovenia	Ljubljana
Slovakia	Bratislava
Finland	Helsinki, Turku Naantali
Sweden	Göteborg Landvetter, Malmö Sturup, Stockholm Arlanda
United Kingdom	Birmingham, Bristol, Edinburgh, Glasgow, Leeds Bradford, Liverpool City, London Heathrow Airport, Luton, Gatwick, Stansted, Manchester, Nottingham East Midlands

Table 3.6: List of the minor airports (comprehensive network) [13]

Member State	Minor airports
Austria	Graz, Innsbruck, Klagenfurt Villach, Linz Wels, Salzburg
Belgium	Charleroi, Oostende Zeebrugge
Bulgaria	Burgas, Gorna Orjahovitsa, Plovdiv, Varna
Czech	Brno
Denmark	Aalborg, Billund, Ronne Bornholm
Germany	Dortmund, Dresden, Erfurt, Hahn, Heringsdorf, Hof Plauen, Karlsruhe K. Baden Baden, Memmingen, Münster Osnabrück, Paderborn P. Lippstadt, Rostock, Weeze, Westerland Sylt
Estonia	Kardla, Kuressaare, Parnu, Tartu
Ireland	Carrickfin, Inishmore, Kerry Farranfore, Knock Connaught, Limerick Shannon, Waterford
Greece	Alexandroupoli, Araxos, Astipalaia, Chania, Chios, Ikaria, Ioannina, Kalamata, Kalymnos, Karpathos, Kassos, Kastelorizo, Kastoria, Kavala, Kefalonia, Kerkyra, Kithira, Kos, Leros, Limnos, Mytilini, Naxos, Nea Anchialos, Paros, Preveza, Rodos, Samos, Santorini, Sitia, Skiathos, Skiros, Syros, Zakinthos
Spain	A Coruna, Almería, Arrecife Lanzarote, Avilés, Asturias, Badajoz, Burgos, El Hierro, Fuerteventura, Girona, Granada, Ibiza, Jerez, La Palma, Leon, Menorca, Melilla, Murcia San Javier, Pamplona, Reus, Salamanca, San Sebastián, Santander, Santiago de Compostela, Tenerife Norte Los Rodeos, Valladolid, Vigo, Vitoria Alava, Zaragoza
France	Ajaccio, Bastia, Beauvais, Biarritz, Brest, Caen, Cayenne, Chalons Vatry, Clermont-Ferrand, Fort de France, La Rochelle, Limoges, Mayotte, Montpellier, Mulhouse-Bale, Nantes Saint Nazaire, Point à Pitre, Saint Denis Gillot, Strasbourg
Croatia	Dubrovnik, Osijek, Pula, Rijeka, Split, Zadar
Italy	Alghero, Ancona, Bari, Bolzano, Brescia, Brindisi, Catania Fontanarossa, Catania Comiso, Firenze, Foggia, Forlí, Lamezia Terme, Lampedusa, Olbia, Pantelleria, Pescara, Pisa, Reggio Calabria, Roma Ciampino, Trapani, Treviso, Trieste, Verona
Cyprus	Pafos
Latvia	Daugavpils, Liepaja, Ventspils
Lithuania	Kaunas, Palanga
Luxembourg	Luxembourg
Hungary	Debrecen, Sarmellek
Malta	Valletta Malta Luqa
Netherlands	Eindhoven, Enschede, Groningen, Maastricht
Poland	Bydgoszcz, Rzeszow
Portugal	Braganza, Corvo, Faro, Flores, Funchal, Horta, Lajes Terceira, Pico, Ponta Delgada, Porto Santo, Santa Maria, Sao Jorge, Vila Real
Romania	Bacau, Baia Mare, Cluj-Napoca, Constanta, Craiova, Iasi, Oradea, Sibiu, Suceava, Tulcea
Slovenia	Maribor, Portoroz
Slovakia	Kosice, Poprad Tatry
Finland	Enontekioe, Ivalo, Joensuu, Jyvaeskylae, Kajaani, Kemi, Kittilae, Kruunupyy, Kuopio, Kuusamo, Lappeenranta, Maarianhamina, Oulu, Pori, Rovaniemi, Savonlinna, Tampere, Vaasa
Sweden	Aengelholm, Arvidsjaur, Gaellivare, Hagfors, Hemavan, Jonkoping, Kalmar, Kiruna, Lulea, Lycksele, Mora, Nyköping, Orebro, Ostersund, Pajala, Ronneby, Skellefteaa, Stockholm, Sundsvall, Sveg, Umea, Vilhelmina, Visby
United Kingdom	Aberdeen, Barra Castlebay, Belfast City, Belfast International, Balivanich Benbecula, Bournemouth, Campbeltown, Cardiff Newport, Durham Exeter, Inverness, Glenegedale Islay, Kirkwall, Liverpool, Londonderry, Newcastle, Newquay, Norwich, Prestwick, Ramsgate, Scilly Isles, Sheffield, Shetland Islands, Southampton, Stornoway, Sumburgh, Isle of Tiree, Wick

3.3 Route analysis

The final step to estimate the volume of potential users is to identify all the candidate routes for the micro-feeder service, obtained through adequate filtering procedure. This procedure is based on three different filtering steps:

- analysis of possible routes;
- comparison with competitors;
- isoline maps.

The main nodes identified in Section 3.2 are the starting point of the route analysis. Each of these steps brings to a routes reduction with respect to all the possible ones. The output of this last phase will bring to the estimation the potential market.

Considering all the identified airports as origin and destination, the possible routes are 124,256. These include international and national routes, with both long and short ranges. According to a specific set of characteristics of the aircraft to be employed (8 passengers, 600 km maximum range), competitiveness of ground transportation means, and other reasonable assumptions, the candidate routes throughout Europe decrease to 401.

In Table 3.7 are listed all the specification of the employed aircraft for this analysis. The main performances and design specifications are based on a previous preliminary sizing activity. The designed hybrid-electric aircraft is the outcome of a MATLAB® code named *Hyperion*, developed and validated using existing aircraft as a reference [61].

3.3.1 Database creation

Before filtering the routes all the data related to the airports must be collected. In order to do this, an implemented MATLAB® code takes in input the TEN-T airports listed by ICAO code and gives back the airports' information using Flight Radar APIs. It has been created a database where each entry contains the airport name, city, country, address and the relative IATA code in addition to the ICAO code.

Subsequently, through HERE Maps APIs the locations of each airport are converted from street names to geo-coordinates, which are an adding value for the above database. This is a crucial step in order to use these last values as input in haversine formula [70], presented below, to compute the distance as the crow flies between two nodes. The airport database creation steps are reported in the first block of the scheme shown in Figure 3.8.

Table 3.7: Hybrid-electric micro-feeder performances and design specifications [61]

Variable	**Value**	**Unit**
Battery		
Battery Specific Power	1	kW/kg
Battery Specific Energy	0.5	kWh/kg
Main data		
Maximum takeoff weight	3,609	kg
Cruise speed	103	m/s
Wing Loading	1,488.9	N/m^2
Power Loading	86.5	N/kW
Total Range	600	km
Aerodynamics		
Wing Surface	23.8	m^2
Wing Span	16.9	m
Polar curve	0.0223 + 0.0323	CL^2
Power		
Maximum	409	kW
Takeoff	400	kW
Climb	293	kW
Cruise	368	kW
Descent	112	kW
Loiter	107	kW
Power generation system and electric motors		
Total Power	388	kW
Average Fuel Consumption	0.2837	kg/kWh
Maximum Temperature	1134	°C
Power Generation System Total Weight	77	kg
Electric motors weight	81	kg
Time breakdown		
Time to Climb	18.8	min
Cruise Time	68.3	min
Time to Descent	20.6	min
Loiter Time	45.0	min
Total Flight Time	107.7 (152.7)	min
Weight breakdown		
Empty Weight	2,145	kg
Payload Weight	913	kg
Battery Weight	412	kg
Fuel Weight	167	kg
Climb Fuel Fraction	13.5	%
Cruise Fuel Fraction	74.0	%
Descent Fuel Fraction	2.5	%
Loiter Fuel Fraction	0	%
Takeoff and landing		
Takeoff Ground Run	325	m
Total Takeoff Distance	540	m
Landing Ground Distance	327	m

3.3.2 Initial analysis

The first filtering step is done through a procedure in which the Flight Radar APIs can be exploited to highlight all the existing routes between all those previously identified nodes and excluding different type of routes. In order to reduce the required computing power, a first filtering step must be done. The constraints considered in this phase, later described in detail, are:

- existing flights;
- routes not of interest for the objective;
- maximum range.

First of all, a MATLAB® program which exploits Flight Radar APIs is able to define which routes already exist and flew by scheduled flights. This code creates a second database with the following information:

- airline IATA and ICAO code;
- source airport and destination airport IATA and ICAO codes;
- 3-letter code for plane type generally used for this flight.

The collected flights between two point could be direct or non-direct flights. According to this data, another column is added to the database including this information. Considering that we are interested only in direct flights, an input constraint is made on the number of stops set on zero.

As said, in the previous section all the main nodes were analyzed defying them as core and comprehensive. These are considered both origin and destination of the routes being examined. A micro-feeder intended as a small aircraft providing a shuttle service from minor airports to a major hub, required the first filter to erase also all those routes which do not correspond to this type of service. For these reasons, all those routes core-core airports and comprehensive-comprehensive airports are neglected. The core-core connections which are those linking major airports are almost all already covered by scheduled flights by most airlines. The second type of connections, those between minor airports are under-served with respect to the previous one. For the specif purpose of this thesis, these type of routes are not considered and another analysis after this can be done on them.

Moreover, the massive computing power required in the next steps bring to neglect all the international routes, even if the respect the previous consideration. However, this is not a big approximation while the candidate aircraft is a micro-feeder which aim is to connect peripheral areas with the core network.

The results lead to focus more on the core-comprehensive national routes. At the end of this first phase, the number of routes has been reduced from 124,256 to 1,519. This is further reduced to 828 neglecting all the existing scheduled flights.

Then, the routes analysis exploits the haversine formula in order to calculate the distance between two nodes, bringing to neglect all those over a certain range. The haversine formula is an important equation in navigation, giving great-circle distances between two points on a sphere from their longitudes and latitudes. It is a special case of a more general formula in spherical trigonometry, the law of haversine, relating the sides and angles of spherical triangles. These names follow from the fact that they are customarily written in terms of the haversine function, given by $hav(\theta) = \sin^2\left(\frac{\theta}{2}\right)$.

For any two points on a sphere, the haversine of the central angle Θ between them is given by:

$$\Theta = \frac{d}{r} \tag{3.1}$$

where d is the distance between the two points and r is the radius of the sphere. In our case, two important assumptions are made. This formula is only an approximation when applied to the Earth, which is not a perfect sphere: the Earth radius R varies from 6356.752 km at the poles to 6378.137 km at the equator. More importantly, the radius of curvature of a north-south line on the earth's surface is 1% greater at the poles ($\approx$ 6399.594 km) than at the equator ($\approx$ 6335.439 km), so the haversine formula cannot be guaranteed correct to better than 0.5%.

The haversine formula hav of Θ is given by:

$$hav(\Theta) = hav(\varphi_2 - \varphi_1) + cos(\varphi_1)cos(\varphi_2)hav(\lambda_2 - \lambda_1) \tag{3.2}$$

where φ_1 and φ_2 are the latitude of point 1 and the latitude of point 2, and λ_1 and λ_2 are the longitude of point 1 and the longitude of point 2.

Finally, the haversine function (half a versine) of an angle θ (applied above to the differences in latitude and longitude) is:

$$hav(\theta) = \sin^2\left(\frac{\theta}{2}\right) = \frac{1 - \cos(\theta)}{2} \tag{3.3}$$

To solve for the distance d, apply the inverse haversine hav^{-1} to the central angle Θ or use the arcsine function:

$$d = r\, hav^{-1}(h) = 2r \arcsin(\sqrt{h}) \tag{3.4}$$

where $h = hav(\Theta)$, or more explicitly:

$$\begin{aligned} d &= 2r \arcsin\Big(\sqrt{hav(\varphi_2 - \varphi_1) + cos(\varphi_1)cos(\varphi_2)hav(\lambda_2 - \lambda_1)}\Big) \\ &= 2r \arcsin\Bigg(\sqrt{\sin^2\Big(\frac{\varphi_2 - \varphi_1}{2}\Big) + cos(\varphi_1)cos(\varphi_2)\sin^2\Big(\frac{\lambda_2 - \lambda_1}{2}\Big)}\Bigg) \end{aligned} \tag{3.5}$$

As previously said, the above equation takes in input the geo-coordinates extracted using Flight Radar APIs and it gives back the distances between each node couples. All the route distances are then filtered according to the aircraft maximum range. As reported in Table 3.7 the hybrid-electric micro-feeder under analysis has a total range equal to 600 km. Those routes over this range are not considered.

All the routes that come out are possible routes that our aircraft can cover. After this second part, the number of routes passes from 828 to 573.

These routes can now be compared to ground competitors' modes.

The first route filtering is reported schematically in the second block called *Filter 1* in Figure 3.8.

3.3.3 Comparison with competitors

Another MATLAB® code has been developed for this section. In the first part, it uses HERE Maps APIs for driving and train transportation information. In the second one, it compares all the transport modes. In this way, we can find where exactly our service can be competitive. It is required an accurate estimation of the minor-major airport travel time of the mode of transportation. It is important to underline that in this section, the travel times compared are those from/to the airports.

It is considered three possible modes of transportation: automobile, train and other public transportation given that scheduled flights were already filtered on the previous step. Then, the code compares directly the micro-feeder travel time with the competitors travel time. Note that additional time due to check-in and traffic are neglected in this preliminary phase. Traffic will not be considered in the entire analysis, with the aim to have ideal cases, however it is an input parameter, as it will be explained later. While check-in will be introduced in the following subsection.

To get all the information for the automobile and public transport modes between two locations, it uses *calculateroute* service. It is a function of HERE Routing API provided by HERE Maps. The MATLAB® section is customizable calling back different options of HERE Maps. In that way, the route calculation and additional information can be adapted to better meet all the different cases. It can tailor the route calculation by:

- defining areas or links that the route must not cross;
- selecting a means of transportation, such as car, public transport, truck or pedestrian;
- selecting a route type such as the fastest or shortest;
- deciding whether to consider current traffic (including incidents and traffic flow), historical traffic, recurring time related restrictions (turns, high-occupancy vehicles, reversible roads), seasonal closures and speed limits, as well as short and long-term closures;
- defining custom penalty parameters to determine the weighting for using specific road attributes in the route calculation, for example, toll road, motorway, boat and rail ferries, public transport;

The code takes in input authentication credentials of the user's HERE Maps account and the geo-coordinate of the start and destination of the first filtered routes. In addition, in the case of travel by car it needs to know whether to take traffic into account. In the case of public transportation, it must be specified the departure time, to choose a public transport routing mode and it is recommended also to include the command related to switch transit lines. In this case study traffic and switch transit lines are not considered. The departure time set at midday in every case.

The second part of the procedure compares the ground travel time with the air travel time. It allows thereby selecting all those routes where the air time is lower than the ground travel time. The hybrid-electric micro-feeder travel time is computed for each route using the relative specification shown in Table 3.7. It comes out that 97,3% of the routes under 60km as the crow flies are better to be traveled by car or train.

Through this analysis, the routes are reduced to 462 from the previous 573 ones. The second route filtering is reported schematically in the third block called *Filter 2* in Figure 3.8.

3.3.4 Isoline maps

A third software code has been developed. This uses again the HERE Maps APIs, this time to calculate and draw the area that can be reached by driving for a given time. The request calculates a certain isoline around the minor airports. This answers the question: “what area can I reach by traveling no more than a time t?” where t is the time to arrive at the minor airport from the starting point. It is defined in order to save time traveling with the micro-feeder rather than with other modes of transport. The fraction of time saved is defined by a parametric gain. The

Figure 3.5: Door to door travel using three modes of transportation

term "mode" here refers to the primary method of transportation an user considers to make a trip from a point of origin (e.g. private residence or workplace) to the point of destination. For example, depending on the choice of origin-destination pair, an individual may decide to drive a car to reach the destination as a preferred mode of transportation (here, the mode would be "automobile"). If the individual chooses to use scheduled train service, the mode would be "train", even though the door-to-door trip would generally require transportation to/from the station. The same consideration is done if the user chooses to use scheduled micro-feeder service.

Comprehensive airports are small regional airports which are located in peripheral or landlocked areas. All the residents around these airports are linked to strategical airports belonging to the core network only by these minor airports or by different modes of transportation.

The outputs of this analysis are isoline maps that are used to define the volume of the potential customers. These are the residents of the considered area.

Within this context, it is considered three possible modes of transportation - automobile, train and micro-feeder. Other public transportations, such as buses, are considered in some cases similar to automobile travel, while in other cases are considered disadvantageous. Each mode may have different combinations of drive, transport and flight segments. Figure 3.5 shows the representative trip segments for each mode of transportation.

For example, an individual seeking to travel from point A to point C using automobile mode the total door-to-door trip includes a direct road trip, which can be the highway, the motorway or the lower capacity roads. The traveler could be facing traffic, possible refueling and loss of time in searching parking around the major hub.

For the public transportation mode, the door-to-door trip is very similar to the automobile mode (A-C). Note that, with this mode, traffic, refueling and parking are avoided, but they are replaced by departure scheduled time and stops.

The door-to-door micro-feeder mode trip includes a driving segment to the nearest minor airport (A-B) which is shorter due to the utilization of smaller regional airports. The passenger will go through the security check and fly to the major hub (B-C), either for a connection to an international airport or to reach his final destination. The boarding time for the micro-feeder operation is expected to be much shorter due to lower passenger volume at the security check of a regional airport. The baggage is expected to stay with the passenger, thereby further reducing the boarding time (embarkation) and the airport exit time (debarkation). The use of a minor airport is going to reduce also the parking time at the airport and the movements inside it.

This composite metric allows us to analyze various modes of transport considering also the loss of time in searching parking, in traffic or in switch transit lines. Nowadays a small-time gain plays a pivotal role in deciding which mode of transport a time-sensitive customer may take to reach the point of destination.

What has been discussed so far is evaluated by a program, which can be considered composed by two section. The first part has the aim to calculate the *time range*, which is the time to move to the minor airport. The second part draw the isoline maps.

In order to draw the isoline map, the MATLAB® code uses *calculateisoline* to calculate the area that can be reached by driving for a given time. *Calculateisoline* is a function provided by HERE Maps. In *Calculateisoline* the following parameters are mandatory, so they have to be put as input in the MATLAB® code:

- HERE Maps user's authentication credentials;
- the geo-coordinates of the start position;
- the mode of travel;
- the time range.

The time range is considered as unknown and it is pre-evaluated by the same code by setting the desired time gain. This time gain is a parametric value which corresponds to the percentage of time that the door-to-door micro-feeder mode trip time is less than the other modes travel time.

This section code has been called *isoline condition.* It takes in input:

- the geo-coordinates of the start and destination position;
- the parametric time gain.

It returns the travel time for each transportation mode and the time range.

Mathematically, the *isoline condition* is the following:

$$t_{AB} + t_{BC} < K\, t_{ACi} \tag{3.6}$$

where:

- i stands for the transportation mode (car or train);
- t_{AB} is the unknown, it is the time to travel from the starting point to the minor airport. It is an input for the *calculateisoline* function;
- t_{BC} is the micro-feeder travel time;
- t_{AC} is the travel time by other transportation modes;

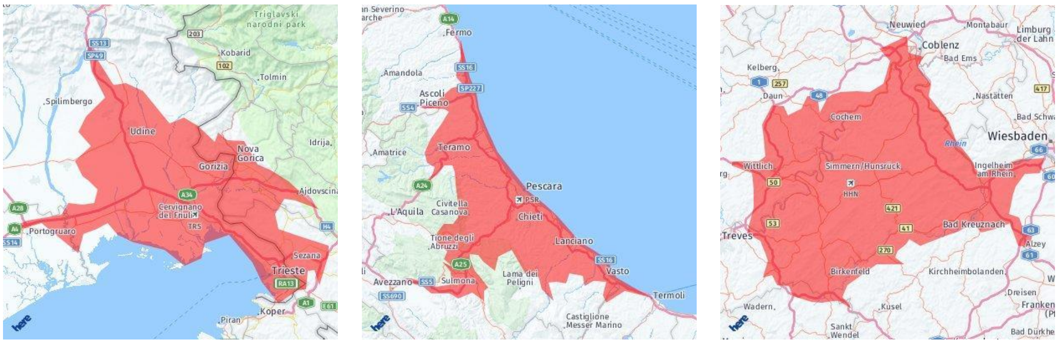


Figure 3.6: Isoline map examples with K=1.5. From left to right: Trieste airport, Pescara airport, Hahn airport

- K is the parametric time gain.

If the route does not respect the isoline condition it is neglected. Moreover, considering that all the comprehensive airports are in peripheral or landlocked areas, a small size area will not cover an acceptable amount of potential users. Knowing that the isoline area is highly dependent on the *time range*, it has been decided to consider a minimum value of 40 min. According to this assumption all those routes with a *time range* lower than 40 min are excluded.

Considering a time gain value of 1.50, this filter reduces the routes from 462 to 401.

Once the time range is evaluated the isoline maps can be drawn. Note that each minor airport is going to have different isoline maps, one for each destination major airport.

Figure 3.6 shows three examples of isoline map, while the third block called *Filter 3* in Figure 3.8 summarizes the third route filtering step.

3.4 Demand estimation

The volume of the potential market for each interested minor airport can be now evaluated. Here follows the procedure to evaluate it.

To suggest potential micro-feeder travelers, it is used the European population distribution data from EUROSTAT database [14] at NUTS3 and the actual European air transport data, both passengers and movements.

In order to avoid an over-estimation of the potential users, two important considerations are done.

- The aim of the micro-feeder is to connect minor airports in a peripheral area with a major airport. A hypothetical passenger will use this service for two possible reasons. In the first one, the passenger wants to reach the major airport because it is his final destination, or at least near it. In the second one, he wants to reach the major airport to get an international flight from it, which is more likely to happen. In this work only the second case is considered.

- Different routes could start from the same comprehensive airport and end in a different major hub. This brings to have different isoline maps for the same minor airport. The following results come out from the minimal coverage area.

The first step in the evaluation of the annual potential market is the evaluation of an annual international passengers fraction per each major airports with respect to the relative country. This is defined as:

$$\beta_{ic} = \frac{AIP_i}{AIP_c} \tag{3.7}$$

where:

- i stands for the major airport;
- c represents the country;
- AIP is the annual international passengers.

Then, the annual passengers per each minor airport are evaluated with respect to the considered isoline map. Their number can be computed as:

$$AP_{jc} = \frac{AIP_j \, RES_{area}}{RES_c} \tag{3.8}$$

where:

- j stands for the minor airport;
- c represents the country;
- AP is the annual passengers;
- RES is the number of residents.

And finally, the annual volume of the annual potential market per each minor airport APM is evaluated as follows:

$$APM_j = AP_j \sum_r \beta_{jr} \tag{3.9}$$

where:

- j stands for the minor airport;
- r represents the major airport linked to the minor airport;

The last block called *Demand Estimation* in Figure 3.8 summarizes the above procedure schematically.

3.5 Case studies

A candidate country is chosen (Figure 3.7), for each of the three categories identified in Table 3.2 and shown in Figure 3.3. Because of the amount of computing power required, the volume of the potential market is defined only for these three case studies. Since they are chosen as representative of their relative cluster, their final results can be expanded to all the countries with some proper adjustments.

For the high and medium ground transportation density, the case studies are Germany and Italy respectively. They have been chosen being positioned at the center of their relative group ranking. While Estonia is chosen for the low ground transportation density due to its particular air transportation condition. Indeed, the national scheduled flights operate all the possible routes in the country. However, these routes are operated by an 18-seater commuter twice a day 5 days of 7 and once a day in the weekend. These flights could be substituted by a micro-feeder which will reduce substantially the emission and the operational costs. This situation exists in many of the countries of this group. Table 3.8 presents the volume of the potential market of Italy and Germany evaluated from the above equations. While the Estonian market is known by data [11, 58]. Area and population for each airport are those relative to the isoline map. Note that the number of the potential market is defined as the number of possible users which will buy a round-trip ticket.

These values must be translated into the number of aircraft to be produced by an aircraft manufacturer company. This will be the primary input for the manufacturer estimation costs in Chapter 4. From these results, considering the number of origin airports (minor airports), the number of routes and an activity that extends 365 days a year, a production quantity of 450 aircraft is considered. Where 280 will be delivered in Germany, 155 in Italy and 15 in Estonia.

There are two main assumptions in the computation of the number of micro-feeders to be produced. The micro-feeders fly always fully booked and they operate twice a day. The first assumption has been made according to the aircraft size. Indeed, analyzing the catchment areas and considering an aircraft of 8-seats, it comes out that the hypothesis of fully booked flights is quite realistic. Instead, the second assumption has been made considering reasonable to assume a yearly utilization

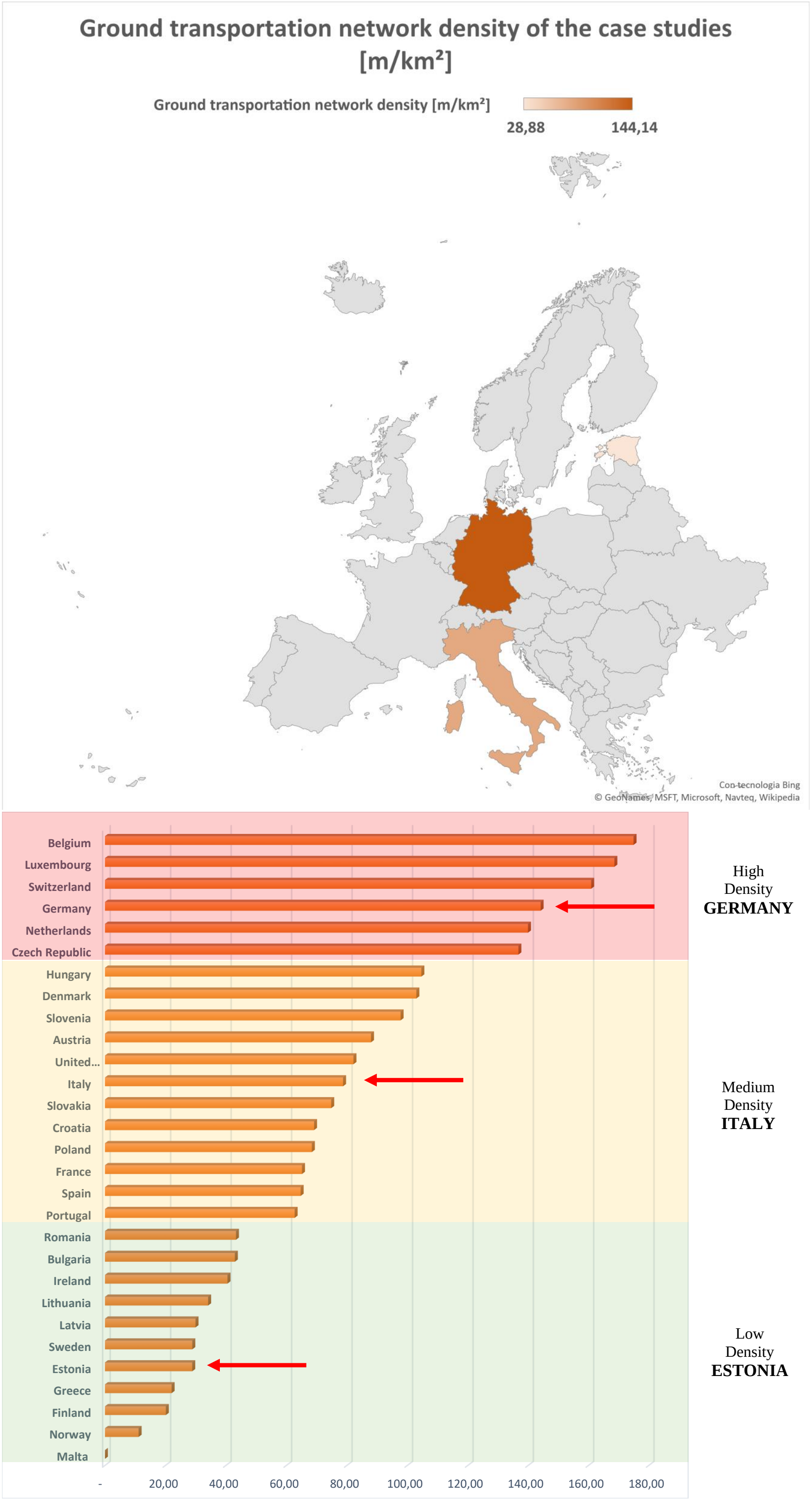


Figure 3.7: Ground transportation network density per case studies, Germany, Italy and Estonia [15, 16]

of 1000h for CS-23 aircraft, which is significantly lower when compared to CS-25. Therefore, this type of organization of the service is quite reasonable.

Obviously, the above case has to be considered as an ideal one, where a single company covers entirely the market under analysis. Furthermore, the production quantity has been evaluated starting from the potential market. Actually, this is a first filtering of the total population. We need to keep in mind that a more depth market exists, the available market, the target market and the already penetrated market.

Table 3.8: Volume of the annual potential market of hybrid-electric micro-feeder for each case studies, Germany, Italy and Estonia

Airports	Area [km^2]	Population 2017	**Annual Potential Market**	**Number of Micro-feeder**
Germany	357,021	82,437,641	1,684,173	280
Erfurt	3,900	747,479	646,829	
Hahn	5,000	2,071,164	692,414	
Rostock	9,400	805,337	218,582	
Hof Plauen	5,300	729,085	126,349	
Italy	301,338	61,219,113	911,078	155
Ancona	3,500	876,775	169,192	
Bolzano	3,900	531,430	162,445	
Brindisi	6,200	1,490,905	38,066	
Foggia	6,600	628,556	129,627	
Lamezia Terme	10,700	1,433,693	45,876	
Pescara	3,800	733,658	214,655	
Trieste	1,900	640,088	151,218	
Estonia	45,227	1,315,635	39,420	15
Kardla	-	-	13,140	
Kuressaare	-	-	13,140	
Tartu	-	-	13,140	

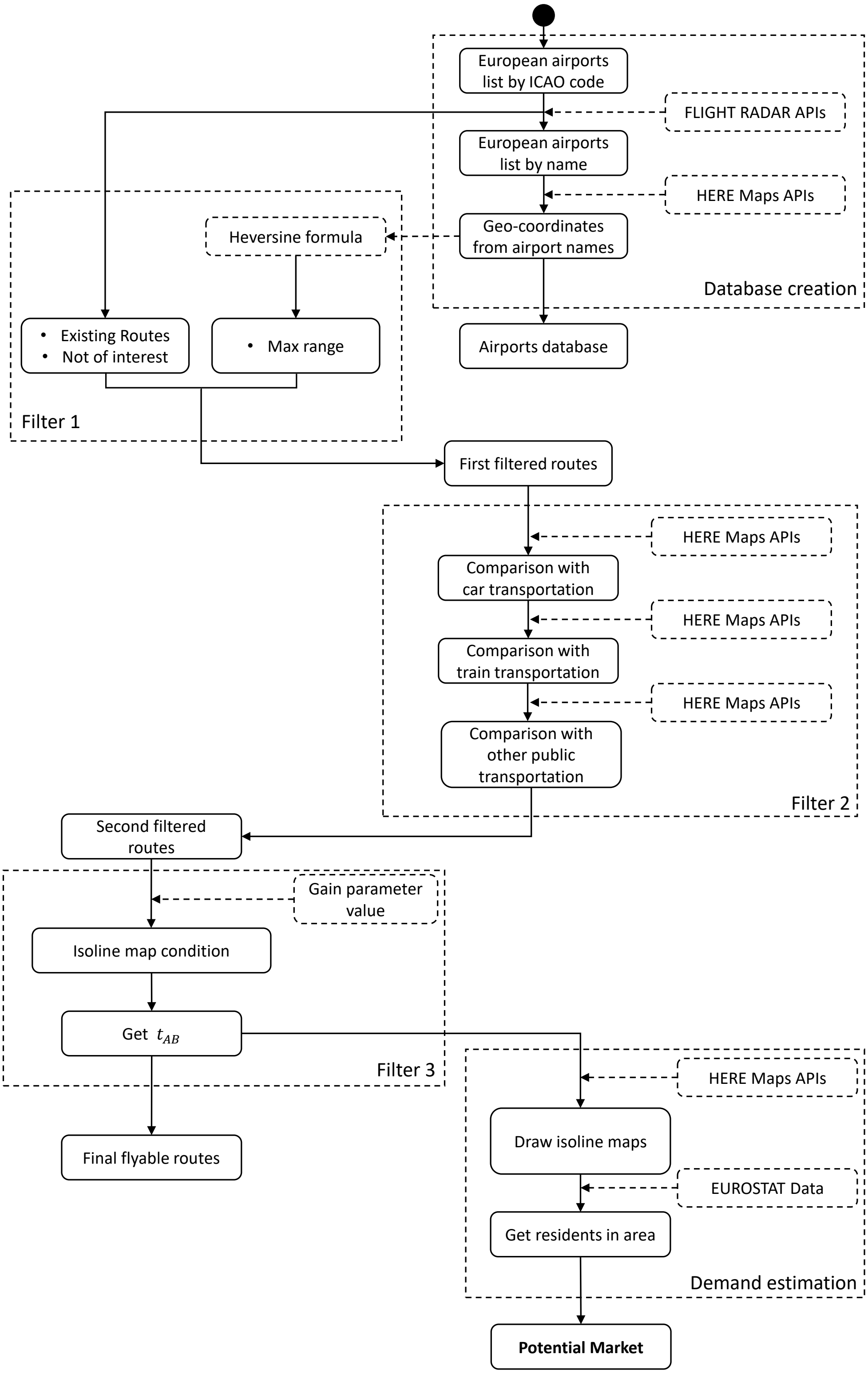


Figure 3.8: Route filtering steps scheme and market analysis output

Chapter 4

Cost analysis

The cost analysis has two targets. These objectives are related to two different points of view. The first one is to determine the investment the manufacturing company must incur to produce a defined quantity. In addition to evaluating its value, it also verifies the soundness of this investment. The second target is analyzing the operating costs that will be met by a hypothetical operator.

It is necessary to distinguish between the cost of producing an aircraft and its selling price. The latter is primarily a function of market forces. It takes in input what comes out from the analysis presented in the previous chapter. The former is the sum of the actual cost of making the aircraft and the share of the development costs allocated to it. Obviously, it will depend on the production quantity which is again a function of market forces. At some time during a long production run of a given type of aircraft, the development costs will have been covered and further cost reduction is dependent upon the improvement of manufacturing techniques. When the cost can be reduced to a level below the price a customer is prepared to pay for the aircraft, the manufacturer makes a profit, but often this does not happen until a large number of the type have been produced.

The prediction of the first cost during the project definition phase is fraught with difficulty. Simple cost models are usually based on aircraft volume and/or mass and are derived empirically from past experience. Unfortunately, in this case, there is no solid past experience to rely on. For this issue, the method presented below is a developed highly modified version of the Development And Procurement Costs of Aircraft (DAPCA), in particular DAPCA-IV, model to estimate the development cost of hybrid-electric micro-feeder.

One of the first components of developing an overall project management plan is to decipher all the individual components required as work activities to develop an overall project schedule of the manufacturing company. Once all the individual work activities have been identified, the project budget and the cost estimation can then be evaluated. For this purpose, in Section 4.1 is explained all the phases involved for an aircraft design, with the activities definition, sequencing and duration estimating. This is the starting point for the costs estimation in Section 4.2. Here, the developed model is presented and all the results which come out from it are shown.

For large projects with a long-term time horizon like aeronautic ones, cost analysis typically fails to account for important financial concerns such as inflation, interest rates, varying cash flows and the present value of money. So, the work includes a prediction and analysis on the prospective financial performance of the project's product. This can be done through different techniques, the Net Present Value (NPV) which is an alternative capital budgeting analysis method is analyzed in Section 4.3. The investment appraisal, which is part of the business case, will if properly structured, improve the decision-making process regarding the desirability or viability of the project.

In the second major part of the cost analysis, all direct operating costs and indirect operating costs are determined. A part of manufacturing and selling airplanes is to persuade potential customers to choose between two competing aircraft designs. In order to bring forth a convincing argument, the analysis focuses also on all the operating costs whose purpose is to provide a true comparison of the cost of ownership between comparable competitive modes of transportation. For the purpose of this thesis, in Section 4.4 only the model developed is presented and according to the case under analysis, different inputs have to be considered.

4.1 Time planning

In general, the aircraft design process involves several distinct phases. These will be now discussed in greater depth. It should be stressed that these differ in detail from company to company, therefore a common process is described.

It all starts with a list of expectations that the new design must meet. It specifies the aircraft capabilities, such as how fast, how far, how high, how many occupants, what payload, and so on (in other words, its mission). The requirements may be as simple as a few lines of expected capabilities or as complex as documents containing thousands of pages, stipulating environmental impact, operating costs, maintainability, hardware, and avionics etc. The *conceptual design* phase formally establishes the initial idea. It absorbs just enough engineering to provide management with a reliable assessment of likely performance, possible looks, basic understanding of the scope of the development effort, including marketability, labor requirements, and expected costs. Typically, in this phase, several characteristics like type of aircraft, mission, technology, aesthetics, a requirement for occupants, certification basis, special aerodynamic features, evaluation of marketability, initial cost estimating are defined. The output of this phase is a conceptual design evaluation, which allows management to decide whether to proceed with the design by entering the preliminary design phase.

The *preliminary design* ultimately answers if the idea is viable. It not only exposes potential problems, as well as possible solutions to those problems but yields a polished loft that will allow a flying prototype to be built. Some of the specific tasks that are accomplished during this phase are:

- detailed geometry development;
- the layout of major load paths;
- weight estimation;
- details of the mission;
- flight performance;
- stability and control;
- evaluation of special aerodynamic features;
- evaluation of certifiability;
- evaluation of mission capability;
- refinement of producibility;
- maintainability;
- preliminary production cost estimation.

Ideally, the output of this phase is the assessment of the features and performance of the preliminary design. If this evaluation is negative the program can be changed or canceled. If positive, a *decision to go ahead* with the fabrication of a Proof-Of-Concept (POC) of the aircraft is usually taken.

The *detail design* process primarily involves the conversion of the preliminary design into something that can be built and ultimately flown. This phase involves a detail design work (structural/mechanical/electronic), the study of technologies, the negotiation with subcontractor and vendor, maintenance procedures planning and a material and equipment logistic. The conclusion of this phase is the final outside mold line and internal structure for the POC. This is generally the beginning of the construction planning, although it almost always begins long before the detail design phase is completed.

The *construction of the first prototype* begins during the detail design phase, once the *configuration is frozen.* At the same time, the production process is being prepared with all its paperwork and quality assurance protocols. For this reason, the intention to produce the design is a very involved process. All the detail designs previously done are now re-visioned. Tooling design and fabrication, and maintenance procedures and refinement of maintainability are accomplished. This phase ending with the first flight of the POC.

A *development program* and testing phase follow a successful completion of the preliminary design. This phase usually begins long before the maiden flight and is usually handled by flight test engineers, flight test pilots, and management. A first ground testing phase is done:

- structural testing;
- aeroelastic testing (ground vibration testing);
- mechanical testing;
- avionics testing.

After the final assembly of the flight-test vehicles, there are different steps: roll-out, first flight and flight testing. Some of the tasks that are accomplished in this phase are listed below:

- establish Aircraft Operating Limitations (AOL);
- establish Pilots' Operating Handbook (POH);
- prepare Master Flight Test Schedule (MFTS);
- establish emergency procedures;
- revise of AOL, POH, MFTS;
- prepare flight readiness review.

The conclusion of the testing phase is a certifiable aircraft. This means the manufacturer understands the risks and scope of the required certification effort and is convinced the certification program can be successfully completed. The output of the development program is actually a certified aircraft.

The production process can now speed up. The first deliveries could be often before the eventual reception of product certificate.

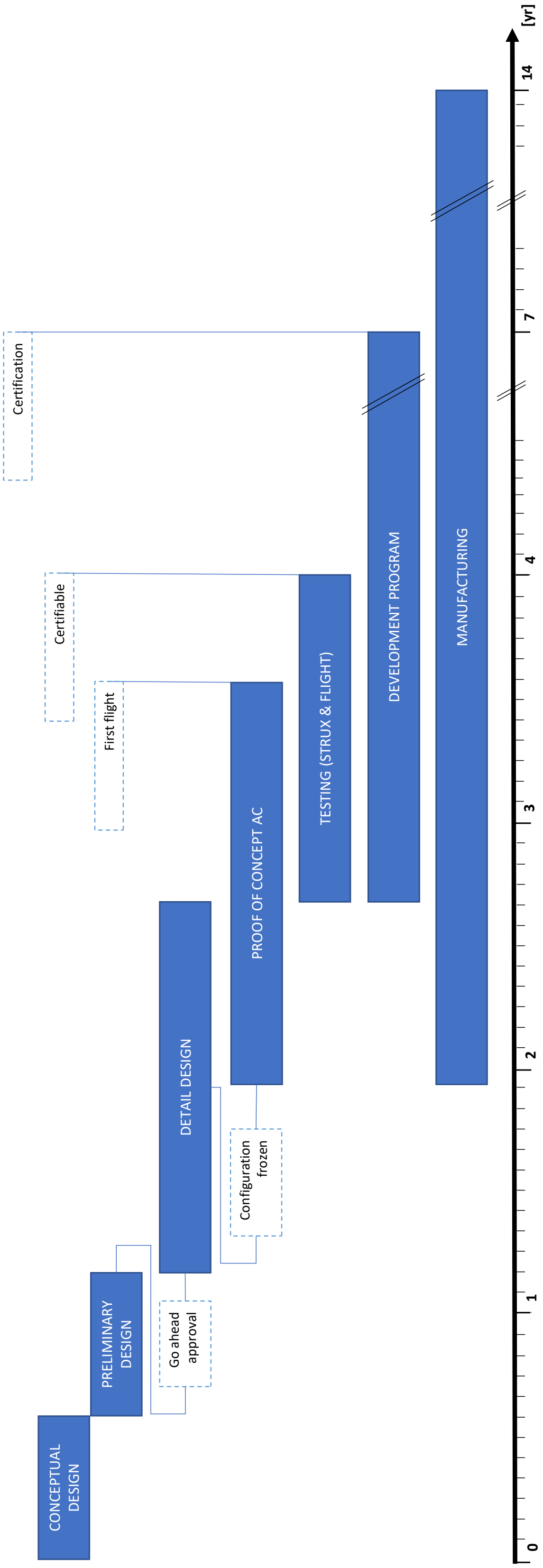
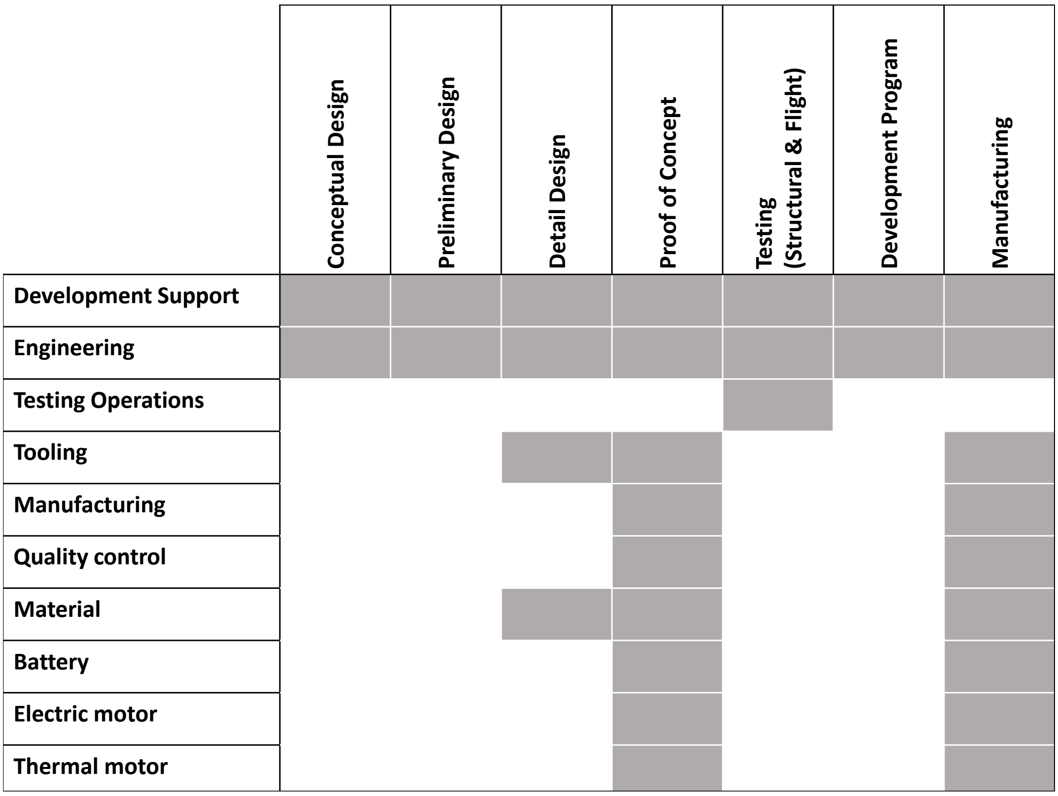


Figure 4.1: Elementary outline of an aircraft project development timeline [68]



	Conceptual Design	Preliminary Design	Detail Design	Proof of Concept	Testing (Structural & Flight)	Development Program	Manufacturing
Development Support	▨	▨	▨	▨	▨	▨	▨
Engineering	▨	▨	▨	▨	▨	▨	▨
Testing Operations					▨		
Tooling			▨	▨			▨
Manufacturing				▨			▨
Quality control				▨			▨
Material			▨	▨			▨
Battery				▨			▨
Electric motor				▨			▨
Thermal motor				▨			▨

Figure 4.2: Cost breakdown structure

Figure 4.1 presents a depiction of the process. The diagram demonstrates the process in a realistic manner, by showing overlapping activities. There is really not a specific date beyond which the previous phase ends and a new one begins, but there is a quite acceptable representative timeline. It also shows important milestones, such as a configuration freeze, go-ahead approval, and acceptance of type certificate. An examination of the project lifecycle diagram will show that each phase can be regarded as a project in its own right, although each will be of very different size and complexity. To be able to control a project, the activity must be broken down further into stages or tasks, which in turn can be broken down further into subtasks or work packages until one can be satisfied that an acceptable control structure has been achieved.

In the following section, the estimation cost will be presented through a developed model. As already said, this model is based on an existing one, which has been modified in order to reflect better the analyzed case. The mentioned existing model estimates the costs by breaking down them into different major contributes.

A relevant advantage is that a cost allocation can be given to each task. The object of all this is to be able to control the project by allocating resources (human, material, and financial). For this purpose Figure 4.2 shows the relation between the activities represented in the project development timeline and the cost contributes.

Note that, actually this breakdown structure is produced in the very early stages of a project, so it will probably not reflect all the tasks that will eventually be required.

4.2 Manufacturer costs

The method presented below uses a highly modified version of the DAPCA (in particular DAPCA-IV) model to estimate the development cost of hybrid-electric micro-feeder. DAPCA-IV establishes special Cost Estimating Relationships (CERs), which are a set of statistical equations that predict aircraft acquisition costs using only basic information like the weight of the bare airframe (without engines, tires, controls, and so on) and maximum level airspeed. The CERs are presented as a set of exponential equations. Two important other models based on DAPCA-IV help in the adaptation of the model, Gudmundsson and Eastlake [23, 35]. Special correction factors are used to account more complicated manufacturing technologies such as the fabrication of tapered wings, complex flap systems[1], pressurization and above all parts of the systems in an hybrid-electric aircraft different from conventional. Since the DAPCA-IV method neither accounts for propulsive devices nor avionics, power plant, batteries and avionics are added later.

The developed program can consider different business cases, so the development costs can be allocated to different production quantities.

4.2.1 Adaptation of cost estimation models

In this subsection, all the assumption and modification done on the existing cost estimation models will be described. The major modifications to the current model are related to:

- design;
- experience effectiveness (learning curve);
- changes in the price level of market basket of consumer goods and services purchased.

Design adjustment factors

In order to adapt the DAPCA model to this work, the two major consideration needed for the design adjustments are:

---

[1] Flaps with fixed hinges are considered to be simple; those with translating hinges, complex.

- design of a micro-feeder;
- design of a hybrid-electric.

This analysis assumes that the manufacturing company already produce conventional airplanes, so with an active and functioning production site. However, all the costs are assumed as costs of an innovative aircraft. A high percentage of the micro-feeder can be considered conventional, such as structure and systems. For these parts tooling and manufacturing estimation costs embrace all of the preparation production as for a conventional aircraft. Considering that the DAPCA model is developed for military aircraft, a modification to account the micro-feeder aircraft must be adopted. Professor Eastlake has already considered this case and he adapted the equations to a GA aircraft. These equations have been then verified applying them to existing cases. A relevant differential is considered in this work when the analysis is done for innovative parts. The additional components increase acquisition cost for hybrid electric aircraft relative to their conventional counterparts. This subdivision is presented in Table 4.1.

These three clusters are defined as follows:

$$\begin{aligned}\textbf{Analogic} = \text{CERs} + & modifications\ to\ account \\ & MICRO-FEEDER\ aircraft\end{aligned} \tag{4.1}$$

$$\begin{aligned}\textbf{Reshaped} = \text{CERs} + & modifications\ to\ account \\ & MICRO-FEEDER\ aircraft \\ & + modifications\ to\ account \\ & HYBRID-ELECTRIC\ aircraft\end{aligned} \tag{4.2}$$

$$\textbf{Ad-Hoc} = Existing\ Cases \tag{4.3}$$

As already said, Professor Eastlake [23] undertook the task of remedying this design education tool deficit in 1986. It presents essentially the same equations. The process of adjusting this set of Cost Estimating Relationship (CER) equations was begun by calculating and tabulating the magnitude of various segments of the design and manufacturing process as given by the cost model. Then, a subjective judgment was made on the question of how time-consuming or difficult each segment is when done on a general aviation aircraft as opposed to being done on a military aircraft. The values selected are indeed subjective but they are logical. Each modification was done by multiplying the original set of equation per a factor related to the required adaptation. Five important factors were considered by Prof. Eastlake:

- aircraft certification;

Table 4.1: Comprehensive list of the costs classified in analogic, reshaped and ad hoc

	Analogic	Reshaped	Ad Hoc
Development Support		X	
Engineering		X	
Flight test operations	X		
Tooling		X	
Manufacturing		X	
Quality Control	X		
Materials	X		
Certify			X
Landing Gear	X		
Avionics		X	
Power Plant			X
Battery			X
Maintenance		X	
Storage	X		
Capital Expenditure	X		
Disposal		X	

- usage of composite;
- wing configuration;
- flap system;
- pressurization.

These factors were confirmed by applying them to existing cases.

In addition to the above factors, this work considers a hybridization factor which takes into account the degree of hybridization. This factor is used in order to consider the differential cost related to the design of a hybrid-electric aircraft. The degree of hybridization p_{hyb} describes the power ratings of the electric motor $P_{EM,max}$ and the thermal motor $P_{TM,max}$ depending on the required total system power $P_{Total,max}$:

$$p_{hyb} = \frac{P_{EM,max}}{P_{Total,max}} = \frac{P_{EM,max}}{P_{EM,max} + P_{TM,max}} \tag{4.4}$$

According to this factor the higher the ratio of hybridization, the more increases the cost of production. The major reason for this is the innovative design. In each following equation, these factors will be differently considered in order to reflect the best their importance in every CERs category.

Unfortunately, this equation cannot be confirmed by applying them to existing cases since the novelty of the product and lack of literature. Therefore, the hybridization factor follows the development of the composite factor. This major assumption has been confirmed by an interview to the R&D Program Manager of a light aircraft manufacturer. The name of the company cannot be disclosed for confidentiality reasons. It is the first aircraft manufacturer to release a fully electric 2-seat aircraft. For their experience in fully electric and hybrid-electric aircraft design their confirmation has been considered viable.

Experience effectiveness adjustment factor

Another change to account is the application of the “learning curve” or quantity discount factor. The cost is adjusted using a special Quantity Discount Factor (QDF) whose value depends on the quantity purchased and the application of a “learning curve” or, more appropriately, experience effectiveness adjustment factor. Increased experience improves the productivity of the technician. This way, 80% experience effectiveness means that if it takes a technician 100 hrs to put together, say, a batch of 10 assemblies, the next batch will only take 80% of that time or 80 hrs, and the next batch will take 64 hrs, and so on. This means that each time the total number of units produced is doubled, the price per unit drops to 80% of the previous unit price. This value was originally applied in the equations but produced incredibly low prices at production quantities in the thousands. Based simply on what produced realistic answers, a 95% learning curve was finally adopted. This factor is computed as follows:

$$F_{QDF} = F_{exp}^{1.4427 \cdot lnN} \tag{4.5}$$

where:

- F_{exp} is the experience effectiveness;
- N is the number of units produced.

It is common to assume an F_{exp} of 80%, but some people with direct experience of a production environment contend this is too optimistic. If the innovation of the project is taking into account, a more realistic value could be F_{exp}=95%. Again, this value has been confirmed through personal communication by the R&D Program Manager of the mentioned light aircraft manufacturer.

Adjustment factor of price level change

This model was originally developed in 1986. Then Professor Eastlake has adapted the costs assuming the cost of living in the year 2012. However, as presented here, the costs are calculated assuming the cost of living in the year 2018. All appropriate constants (excluding exponentials) have been updated to reflect this. This means that for later years, the costs must be adjusted to reflect current values. This is usually done through the application of the Consumer Price Index (CPI), known informally as the cost of living index. This information can be obtained from the website of the Bureau of Labor Statistics [46, 69]. This means that for future works, the CPI must be updated relative to the year 2018.

4.2.2 Development cost estimation of a hybrid-electric micro-feeder

As said, the model estimates the costs by breaking down them into different major contributes. Each one of them will be defined in the following subsection. The first phase of the method is to estimate man-hours for three important areas of the project: engineering, tooling, and manufacturing. Once the number of hours has been determined, the next step is to estimate costs by multiplying these with rates in currency per hour. Then other additional costs are considered directly as a function of the units produced. Finally, other fixed costs are evaluated, these are not a function of units produced or labor man-hours. Once these steps are completed, it is possible to estimate the price per unit, number of units to break-even, and other factors of interest.

Note that the certification costs are embedded in the following costs. Only the type certification is considered. Other certifications related to the manufacturer have to be evaluated and added separately.

In the following subsections, each major cost contributes are presented with a small description of the relative project area, the estimating equations and the input description. The last subsection shows the model output of this case study with the relative initial hypotheses.

Engineering

Engineering hours include the airframe design and analysis, test engineering, configuration control, and system engineering. Engineering hours are primarily expected during RDT&E, but there is some engineering effort through production. The engineering effort performed by the airframe contractor to integrate the power plant and avionics systems into the aircraft is included under engineering hours. On the other hand, the actual engineering effort requested to design and produce power plant and avionics is not included. Those items are treated as purchased equipment. Engineering support of tooling and production planning are included in those areas instead of in engineering.

The number of engineering man-hours required to design the aircraft and perform the necessary RDT&E can be estimated from the following expression:

$$\begin{aligned} H_{ENG} = & 4.86 \cdot W_{airframe}^{0.777} \cdot V_H^{0.894} \cdot N^{0.163} \cdot F_{CF} \cdot F_{COMP} \cdot \\ & \cdot F_{PRESS} \cdot F_{QDF} \cdot F_{HYB} \end{aligned} \tag{4.6}$$

where:

- $W_{airframe}$ is the weight of the structural skeleton;
- V_H is the maximum speed in level flight in KTAS;
- N is the number of planned aircraft to be produced over a 5-year period;
- $F_{CF} = 1$ if a simple flap system, $= 1.03$ for a complex flap system;
- $F_{COMP} = 1 + f_{comp}$, a factor to account for the use of composites in the airframe;
- f_{comp} is the fraction of airframe made from composites ($= 1$ for a complete composite aircraft);
- $F_{PRESS} = 1$ for an unpressurized aircraft, $= 1.03$ if pressurized;
- $F_{HYB} = 1 + p_{hyb}$, a factor to account for the hybridization degree of the aircraft.

Note that the structural skeleton weighs far less than the empty weight of the aircraft. This weight can be approximated by considering the empty weight without engines, avionics, seats, furnishing, control system, and other components. The total cost of engineering the aircraft can be computed as follows:

$$C_{ENG} = 2.0969 \cdot H_{ENG} \cdot R_{ENG} \cdot CPI_{2018} \cdot C_{CONV} \tag{4.7}$$

where:

- R_{ENG} is the rate of engineering labor in € per hour;
- CPI_{2018} is the consumer price index relative to the year 2018;
- C_{CONV} is the exchange rate from dollar to euro.

The constant 2.0969 is the CPI for the years 1986 to 2012, which is when the CERs models were developed, while CPI_{2018} reflects the changes of the consumer price index relative to 2018. The exchange rate is needed since the model is developed to come out the result in dollars. The following equations have been corrected as well.

Development Support

Development support costs C_{DEV} are the cost of overheads, administration, logistics, human resources, facilities maintenance personnel and similar entities required to support the development effort, those to calculate and pay salaries, and other necessary tasks. These are expressed by:

$$\begin{aligned} C_{DEV} =& 95.24 \cdot W_{airframe}^{0.630} \cdot V_{H}^{1.300} \cdot CPI_{2018} \cdot F_{CF} \cdot F_{COMP} \\ & \cdot F_{PRESS} \cdot F_{HYB} \cdot C_{CONV} \end{aligned} \tag{4.8}$$

where:

- F_{CF} = 1 if a simple flap system, = 1.01 for a complex flap system;
- $F_{COMP} = 1 + 0.50\ f_{comp}$, a factor to account for the use of composites in the airframe;
- f_{comp} is the fraction of airframe made from composites (= 1 for a complete composite aircraft);
- F_{PRESS} = 1 for an unpressurized aircraft, = 1.03 if pressurized;
- $F_{HYB} = 1 + 0.50\ p_{hyb}$, a factor to account for the hybridization degree of the aircraft.

Flight Test Operations

Flight-test costs cover all the costs incurred to demonstrate airworthiness for civil certification. Costs for the flight-test aircraft are included in the total production-run cost estimation. They include planning, instrumentation, flight operations, data reduction, and engineering and manufacturing support for flight testing. The flight test operations does not change according to the power plant of the tested aircraft. Therefore, the flight test operation costs are the same of a conventional GA aircraft and they are evaluated as follows:

$$C_{FT} = 2606.51 \cdot W_{airframe}^{0.325} \cdot V_{H}^{0.822} \cdot N_{PROT}^{1.210} \cdot CPI_{2018} \cdot C_{CONV} \tag{4.9}$$

where N_{PROT} is the number of prototypes.

Tooling

Tooling hours embrace all of the preparation all the preparation for production: design and fabrication of the tools and fixtures, preparation of molds and dies, programming for numerically-controlled manufacturing, and development and fabrication of production test apparatus. Tolling hours also cover the ongoing tooling support during production. The number of tooling man-hours required is computed as follows:

$$\begin{aligned} H_{TOOL} = & 5.99 \cdot W_{airframe}^{0.777} \cdot V_H^{0.696} \cdot N^{0.263} \cdot F_{TAPER} \cdot F_{CF} \cdot F_{COMP} \\ & \cdot F_{PRESS} \cdot F_{QDF} \cdot F_{HYB} \end{aligned} \tag{4.10}$$

where:

- Q_m is the estimated production rate in the number of aircraft per month (=N/months);
- $F_{TAPER} = 1$ for a tapered wing, 0.95 for constant-chord wing;
- $F_{CF} = 1$ if a simple flap system, $= 1.02$ for a complex flap system;
- $F_{COMP} = 1 + f_{comp}$, a factor to account for the use of composites in the airframe;
- f_{comp} is the fraction of airframe made from composites ($= 1$ for a complete composite aircraft);
- $F_{PRESS} = 1$ for an unpressurized aircraft, $= 1.01$ if pressurized;
- $F_{HYB} = 1 + p_{hyb}$, a factor to account for the hybridization degree of the aircraft.

Note that some recurring variables have new values.

The tooling requires industrial and manufacturing engineers for the design work and technicians to fabricate and maintain. The total cost of tooling the aircraft can be computed as follows:

$$C_{TOOL} = 2.0969 \cdot H_{TOOL} \cdot R_{TOOL} \cdot CPI_{2018} \cdot C_{CONV} \tag{4.11}$$

where R_{TOOL} is the rate of tooling labor in € per hour.

Manufacturing

Manufacturing labor is the direct labor to fabricate the aircraft, including forming, machining, fastening, subassembly fabrication, final assembly and purchased part installation. The number of man-hours required to build the aircraft:

$$\begin{aligned} H_{MFG} =& 7.37 \cdot W_{airframe}^{0.820} \cdot V_H^{0.484} \cdot N^{0.641} \cdot F_{CF} \cdot F_{COMP} \\ & \cdot F_{QDF} \cdot F_{HYB} \end{aligned} \tag{4.12}$$

where:

- $F_{CF} = 1$ if a simple flap system, $= 1.01$ for a complex flap system;
- $F_{COMP} = 1 + 0.25\ f_{comp}$, a factor to account for the use of composites in the airframe;
- $F_{HYB} = 1 + 0.25\ p_{hyb}$, a factor to account for the hybridization degree of the aircraft.

The following equation entails the total cost of manufacturing labor required to produce the aircraft:

$$C_{MFG} = 2.0969 \cdot H_{MFG} \cdot R_{MFG} \cdot CPI_{2018} \cdot C_{CONV} \tag{4.13}$$

where R_{MFG} is the rate of manufacturing labor in € per hour.

Quality control

Quality control is actually a part of the manufacturing but is estimated separately. It includes receiving an inspection, production inspection, and final inspection. Quality control inspects tools and fixtures as well as aircrafts sub-assemblies and completed aircraft. They are evaluated by:

$$\begin{aligned} C_{QC} =& 0.133 \cdot 2.0969 \cdot H_{MFG} \cdot R_{MFG} C_{MFG} \cdot F_{COMP} \\ & \cdot F_{HYB} \cdot CPI_{2018} \cdot C_{CONV} \end{aligned} \tag{4.14}$$

where:

- $F_{COMP} = 1 + 0.50\ f_{comp}$, a factor to account for the use of composites in the airframe;
- $F_{HYB} = 1 + 0.50\ p_{hyb}$, a factor to account for the hybridization degree of the aircraft.

Materials

This is the cost of raw material (aluminum sheets, pre-impregnated composites, etc.) required to fabricate the airplane:

$$
\begin{aligned}
C_{MAT} = & 23.066 \cdot W_{airframe}^{0.921} \cdot V_H^{0.621} \cdot N^{0.799} \cdot F_{CF} \cdot F_{PRESS} \cdot F_{QDF} \\
& \cdot F_{HYB} \cdot CPI_{2018} \cdot C_{CONV}
\end{aligned}
\tag{4.15}
$$

where:

- $F_{CF} = 1$ if a simple flap system, $= 1.02$ for a complex flap system;
- $F_{PRESS} = 1$ for an unpressurized aircraft, $= 1.01$ if pressurized;
- $F_{HYB} = 1 + 0.50\ p_{hyb}$, a factor to account for the hybridization degree of the aircraft.

The total cost to certify is the cost of engineering, development support, flight test, and tooling (assuming production tooling is used to produce at least one of the prototypes):

$$
C_{CERT} = C_{ENG} + C_{DEV} + C_{FT} + C_{TOOL} \tag{4.16}
$$

Avionic

Gudmundsson [35] suggests adding 60,000 \$ (in 2012 US dollars) per airplane in absence of more accurate information. This value has to be considered in 2018 us dollars through the CPI_{2018} and then converted using C_{CONV}. The consider cost of the avionics is 58,000 € per aircraft.

Thermal motor

The cost of the engine depends on the number and type of engines (piston, turboprop or turboshaft, turbojet, or turbofan). The previous preliminary sizing activity on which we rely on involves the installation of a turboshaft generator. The relative equation is:

$$
C_{PP} = 377.4 \cdot N_{PP} \cdot P_{TM,max} \cdot CPI_{2018} \cdot C_{CONV} \tag{4.17}
$$

According to data presented in Table 3.7 the cost per thermal engine is 68,570 €.

Battery and electric motor

The cost aspects of the electric components are determined. Since the commercialization of such high-power components is not reached, there are no sources for a reliable pricing structure. The costs are compared to the exemplary High-Temperature Superconductors (HTS) projects, in which high power components were realized.

As reported in [38], two reference values are available in the literature: a 7.5 MW HTS motor for a boat costs 46.67 €/kW [62, 67] and a 12 MW HTS wind energy generator which costs 210.25 €/kW. Here, a higher price than the average value of these two references is taken into account due to higher certification costs in the aviation industry. Costs of 150 €/kW are assumed for a high-power electric motor.

The costs for the power electronics are derived from the motor costs, because of lack of information. The cost ratio between power electronics and electric motors is examined for exemplary applications in an electric vehicle and a wind energy plant [38]. In reference [44], the authors investigate the costs of an electric car and use a cost ratio of 0.3. In wind energy plants the power electronics have a higher share of total costs and the cost ratio is 0.713 as reported in [6]. A study [38] conducted by Institute of Electric Power Systems and Aeronautics Research Centre Niedersachsen reports an average cost ratio of 0.5 for hybrid-electric aircraft. This leads to power electronics costs of 75 €/kW. Other costs for the cables and further electric components are not considered.

Also, the costs of the battery systems are examined. Li-S cells material costs are projected to be around 70–130$ per kWh. The overall battery pack costs are targeted to reach 150$ per kWh as reported in [37].

Model output

Once the estimating model is established all the cost can be evaluated by setting all the input values. In order to do that some assumption must be done.

- 30% of the airframe structure is considered composed by composite.
- It is assumed to construct two prototypes during the POC phase.
- The production site is assumed to be in Slovenia considering a company as Pipistrel as manufacturing company.
- The rates for engineering, tooling labor and manufacturing labor are assumed as average Slovenian quantities.
- Avionics, engines and batteries are assumed purchased by external suppliers.

As said at the beginning of the chapter, the production quantity has been evaluated from the market analysis done before. The three case studies potential market summarized in Table 3.8 is defined as the number of possible users which will buy a two ways ticket, departure and arrival. From those values, considering the number of origin airports (minor airports), the number of routes and an activity that extends 365 days a year, a production quantity of 450 aircraft is considered. Considering 280 for Germany, 155 for Italy and 15 for Estonia.

Table 4.2: Input values for costs estimation for a hydrid-electric micro-feeder

Variable		Value	Unit
Airframe weight	$W_{airframe}$	1147	kg
		2529	lb
Maximum speed in level flight (TAS)	V_H	103	m/s
		200	kn
Degree of hybridization	p_{HYB}	0.273	
Electric motor maximum power	$P_{EM,max}$	409	kW
Thermal motor maximum power	$P_{TM,max}$	388	kW
Total production quantity	N	450	
Prototype production quantity	N_{PROT}	2	
Number of engines	N_{ENG}	2	
Experience effectiveness factor	F_{EXP}	0.95	
Airframe composite fraction	f_{comp}	0.30	
Simple flap system factor	F_{CF}	1	
Unpressurized factor	F_{PRESS}	1	
Tapered wing factor	F_{TAPER}	1	
Engineering rate	R_{ENG}	43	€
Manufacturing rate	R_{MFG}	23	€
Tooling rate	R_{TOOL}	28	€
Consumer price index (November 2018)	CPI_{2018}	1.12	
Exchange rate (November 2018)	C_{CONV}	0.86	
Electric motor cost	C_{EM}	150	€/kW
Electric generator cost	C_{EG}	75	€/kW
Battery cost	C_{BAT}	150	€/kWh

Table 4.3: Cost estimation per important areas of the project

	Unit	Value
Development support	€	24,239,488
Engineering	€	64,825,262
Flight test operations	€	6,530,395
Tooling	€	39,267,650
Manufacturing	€	112,120,217
Quality control	€	18,942,373
Materials	€	91,127,880
Battery	€	12,154,445
Electric motor	€	41,883,906
Thermal motor	€	98,991,096
TOTAL DC	€	510,082,712
COST per unit	€	1,133,520
PRICE per unit	€	1,473,570

Table 4.4: Cost per year estimation per important areas of the project (from the start date to 6th year)

	Unit	0	1	2	3	4	5	6
Development support	€	2,423,949	2,423,949	2,423,949	2,423,949	2,423,949	2,181,554	2,181,554
Engineering	€	6,482,526	6,482,526	6,482,526	6,482,526	6,482,526	5,834,274	5,834,274
Flight tests	€	-	-	979,559	4,571,277	979,559	-	-
Tooling	€	-	5,497,471	9,424,236	5,497,471	1,963,383	1,963,383	1,963,383
Manufacturing	€	-	-	121,080	242,160	121,080	121,080	121,080
Quality control	€	-	-	1,515,390	1,515,390	1,515,390	1,515,390	1,515,390
Materials	€	-	-	98,410	196,820	98,410	98,410	98,410
Battery	€	-	-	13,126	26,252	13,126	13,126	13,126
Electric motor	€	-	-	45,231	90,462	45,231	45,231	45,231
Thermal motor	€	-	-	106,902	213,804	106,902	106,902	106,902
TOTAL DC	€	8,906,475	14,403,946	21,210,409	21,260,110	13,749,556	11,879,349	11,879,349

Table 4.5: Cost per year estimation per important areas of the project (from 7th year to the 14th)

	Unit	7	8	9	10	11	12	13	14
Development support	€	969,580	969,580	969,580	969,580	969,580	969,580	969,580	969,580
Engineering	€	2,593,010	2,593,010	2,593,010	2,593,010	2,593,010	2,593,010	2,593,010	2,593,010
Flight tests	€	-	-	-	-	-	-	-	-
Tooling	€	1,963,383	1,963,383	1,963,383	1,963,383	1,963,383	1,570,706	1,570,706	-
Manufacturing	€	2,421,603	7,264,809	14,529,618	21,794,427	21,794,427	21,794,427	21,794,427	-
Quality control	€	1,515,390	1,515,390	1,515,390	1,704,814	1,704,814	1,704,814	1,704,814	-
Materials	€	1,968,205	5,904,614	11,809,229	17,713,843	17,713,843	17,713,843	17,713,843	-
Battery	€	262,515	787,545	1,575,090	2,362,635	2,362,635	2,362,635	2,362,635	-
Electric motor	€	904,620	2,713,860	5,427,720	8,141,580	8,141,580	8,141,580	8,141,580	-
Thermal motor	€	2,138,037	6,414,110	12,828,220	19,242,330	19,242,330	19,242,330	19,242,330	-
TOTAL DC	€	14,736,342	30,126,300	53,211,238	76,485,600	76,485,600	76,092,924	76,092,924	3,562,590

This last inner loop is what we actually considered in the Estonian case, where this hybrid-electric micro-feeder will replace an existing service.

In Table 4.2 all the inputs set for the costs estimation are shown.

The output of this phase is summarized in Table 4.3. These are distributed over the years, from the start date of the project during the entire production time Tables 4.4 and 4.5. This subdivision will play a role part in the next section. The cost allocation is a function of the development timeline presented in Figure 4.1 and in the breakdown structure in Figure 4.2. Each cost segment will be differently weighted inside each timeline block.

Based primarily on the widely quoted testimony of the R&D Program Manager of the light aircraft manufacturer interviewed, the estimate is that product price increases the cost by 30% for unit costs. However, this value is a user input in the developed model.

4.3 Investment appraisal

The selection of the right project for future investment is a crucial decision for long-term survival of a company. The selection of the wrong project might well precipitate project failure, leading to company liquidation. A numeric model is usually financially focused and qualifies the project in terms of time to repay the investment (payback time) or return the investment. Non numeric models look at a much wider view of the project. The main purpose of these models is to lead to project selection. Companies tend to prefer financial models and often select solely on profitability. In an investment appraisal, only the incremental income and expenses attributed directly to the project under consideration should be included. An important indication of the success of an aircraft program is the NPV. It is a measure of the value or worth adding to the company by carrying out the project. If the NPV is positive the project merits further consideration. When ranking projects, preference should be given to the project with the highest NPV.

The NPV is actually the summation of the present (now) value of a series of present and future cash flows. Future cash flows should be *actualized* in order to have them comparable with the money spent today. The present value of a single cash flow in the year y is obtained as:

$$C_{FLOW} = C_{IN} - C_{OUT} \tag{4.18a}$$

$$PV = D \cdot C_{FLOW} \tag{4.18b}$$

$$D = \frac{1}{(1 + WACC)^{y}} \tag{4.18c}$$

where:

- $WACC$ is the Weighted Average Cost of Capital (WACC) which measures the nominal post-tax opportunity cost of funds invested, in other words, it is the rate that a company is expected to pay on average to all its security holders to finance its assets. It can be calculated as the summation of the cost of equity and the cost of debt, multiplied per the equity weight and the debt weight relatively;
- y is the number of years from the start date of the project.

Note that the PV is the Discounted Net Cash Flow (DNCF) as it called in Table 4.6 and 4.7. The NPV on investment is defined as the sum that results when the expected investment and operating costs of the project (discounted) are deducted from the discounted value of the expected revenues:

$$NPV = \sum_{\tau=0}^{y} \frac{C_{FLOW}(\tau)}{(1+WACC)^{\tau}} \tag{4.19}$$

There are advantages and disadvantages in using NPV. The advantages are:

- introduction of the time value of money;
- it expresses all future cash flow in today's values, which enables direct comparisons;
- consideration of inflation and escalation;
- the possibility to look at the entire project from start to finish;
- the possibility to simulate a project through a "what-if" analysis using different values;
- it gives more accurate profit and loss forecast than non discounted cash flow calculations.

While on the other hand there are different disadvantages:

- the accuracy of the method is limited by the accuracy of the predicted cash flows and interest rates;
- excludes non-financial data;
- it uses a fixed rate over the duration of the project.

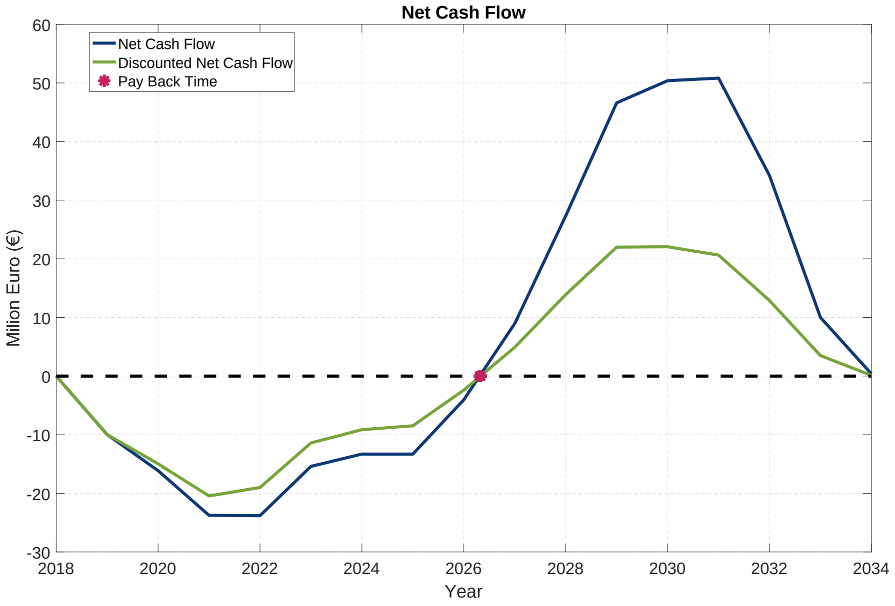


Figure 4.3: Net Cash Flow

These calculations could be refined alongside them with other methods and calculations which will not be considered in this work.

Table 4.6 and 4.7 shows the NPV evaluated for this analysis. The case studies have been carried out considering a production in Slovenia. In the current year, the tax rate in Slovenia is 36% [27, 65]. On the other hand, the $WACC$ has been set to 8%. This value has been obtained from the mean rate of different real aircraft manufacturers during the last 10 years [36, 53]. The cumulated Net Cash Flow is shown in Figure 4.3. The non-discounted one is compared to the discounted one (after the actualization). It is also possible to evaluate the payback time, the point in which the revenues related with the investment cover the starting cost of the investment. The payback time is evaluated as follows:

$$\sum_{\tau=0}^{PBT} C_{FLOW}(\tau) = 0 \tag{4.20}$$

An improvement to the project could be done by considering a different type of payment, i.e. a certain percentage of anticipation. In the following results shown in Tables 4.6 and 4.7 have been computed considering a cash on delivery. Usually, this is not the payment method used in aviation, but in absence of further information is a good approximation in order to avoid an overestimation of the project. In other words, if the project is positive with this approximation, it would be with a partial anticipation of the final aircraft price by the customer.

Table 4.6: Cost per year estimation per important areas of the project (from the start date to 7th year)

	0	1	2	3	4	5	6	7
Produced quantity	0	0	0	0	0	0	0	10
Sold quantity	0	0	0	0	0	0	0	9
Cash in	-	-	-	-	-	-	-	12,471,965
Sales	-	-	-	-	-	-	-	13,605,780
AR	-	-	-	-	-	-	-	1,133,815
Revenue	11,878,421	19,210,308	28,287,977	28,354,263	18,337,558	15,843,294	15,843,294	19,653,619
Cash out	9,976,375	16,134,237	23,758,334	23,814,005	15,401,237	13,306,369	13,306,369	16,506,562
DC	8,906,475	14,403,946	21,210,409	21,260,110	13,749,556	11,879,349	11,879,349	14,736,342
AP	-	-	-	-	-	-	-	-
Investment	-	-	-	-	-	-	-	-
Depreciation	-	-	-	-	-	-	-	-
EBIT	2,971,946	4,806,362	7,077,568	7,094,153	4,588,003	3,963,945	3,963,945	4,917,277
Taxes	1,069,900	1,730,290	2,547,925	2,553,895	1,651,681	1,427,020	1,427,020	1,770,220
NCF	-9,976,375	-16,134,237	-23,758,334	-23,814,005	-15,401,237	-13,306,369	-13,306,369	-4,034,596
ATC rate	1.00	0.93	0.86	0.80	0.74	0.69	0.64	0.59
DNCF	-9,976,375	-14,966,824	-20,444,592	-19,009,739	-11,404,613	- 9,140,412	-8,479,046	-2,384,892
NPV	4,181,780							
NPV/SALES	0.62 %							

Table 4.7: Cost per year estimation per important areas of the project (from 8th year to the 14th)

	8	9	10	11	12	13	14	15
Produced quantity	30	60	90	90	90	80	0	0
Sold quantity	30	60	90	90	90	78	3	0
Cash in	42,707,032	86,925,818	132,278,419	136,057,802	136,057,802	119,428,515	13,983,719	377,938
Sales	45,352,601	90,705,201	136,057,802	136,057,802	136,057,802	117,916,762	4,535,260	-
AR	3,779,383	7,558,767	11,338,150	11,338,150	11,338,150	9,826,397	377,938	-
Revenue	40,178,956	70,966,963	102,007,600	102,007,600	101,483,894	101,483,894	4,751,368	-
Cash out	33,745,257	59,603,299	85,673,520	85,673,520	85,233,673	85,233,673	3,990,550	-
DC	30,126,300	53,211,238	76,485,600	76,485,600	76,092,924	76,092,924	3,562,590	-
AP	-	-	-	-	-	-	-	-
Investment	-	-	-	-	-	-	-	-
Depreciation	-							
EBIT	10,052,656	17,755,724	25,522,000	25,522,000	25,390,970	25,390,970	1,188,778	-
Taxes	3,618,956	6,392,061	9,187,920	9,187,920	9,140,749	9,140,749	427,960	-
NCF	8,961,776	27,322,519	46,604,899	50,384,282	50,824,129	34,194,842	9,993,168	377,938
ATC rate	0.55	0.51	0.47	0.44	0.41	0.38	0.35	0.32
DNCF	4,914,100	13,897,987	21,990,948	22,054,068	20,636,917	12,880,025	3,491,729	122,501
NPV	4,181,780							
NPV/SALES	0.62 %							

4.4 Operator costs

The following model developed for the hybrid-electric micro-feeder service is again an adapted model. The model mixes the Eastlake model for GA aircraft [23], the Gudmundsson model [35], Hoelzen's model [38] and a research of RWTH Aachen University [45].

As some parts of the operating costs can only be calculated per flight or per year, it is necessary to make assumptions regarding the operating model of the aircraft. This includes the flight cycles, average operational distance, the flight hours per year, and the life expectancy of the aircraft. Battery depreciation is considered separately. The direct operating costs are divided into fuel, maintenance, operating crew, and charges. The indirect operating costs consist of aircraft depreciation, insurance, and capital expenditure. Additionally, a Selling General and administration (SGA) contribution is considered to reflect the total service costs rather than only the costs of goods sold.

For the purpose of this thesis, only the model developed is presented and according to the case analyzed by the user, different inputs have to be considered.

Energy

Fuel and electricity costs are calculated taking the fuel burn F_{burn}, the fuel price C_{fuel}, the required battery energy E_{bat} and the electricity price C_{ele}:

$$C_{energy} = N_{flight} \cdot (F_{burn} \cdot C_{fuel} + E_{bat} \cdot C_{ele}) \tag{4.21}$$

Maintenance

Specific maintenance costs C_{AM} include the maintenance of the aircraft C_{AMac}, engine overhaul C_{OVER}, annual inspections C_{INSP}, and storage C_{STOR}. These costs are estimated as follows [35]:

$$C_{AM} = C_{AMac} + C_{OVER} + C_{STOR} \tag{4.22}$$

where:

$$C_{AMac} = 2.02 \cdot R_{AP} \cdot Q_{FLGT} \tag{4.23}$$

$$C_{OVER} = 7.5 \cdot N_{PP} \cdot Q_{FLGT} \cdot F_{HYB} \cdot C_{CONV} \tag{4.24}$$

$$C_{STOR} = 12 \cdot R_{STOR} \tag{4.25}$$

where:

- R_{AP} is the fully loaded hourly cost rate for certified mechanic;

- $F_{HYB} = 1 + p_{hyb}$;
- R_{STOR} is the storage rate which depending on the size of hangar space needed.

Note that the F_{HYB} is considered as an additional factor for electric engines overhaul costs because the original formula only applied to piston engines. It is assumed that the overhaul costs for electric motors are less than piston engines.

Crew

In this work, for a micro-feeder, a crew consists of one pilot. However, it is at the discretion of the operator company. The crew costs are expressed by:

$$C_{CREW} = N_{CREW} \cdot R_{CREW} \cdot Q_{FLGT} \tag{4.26}$$

where:

- R_{CREW} is the hourly crew rate.

Fees

In addition to these costs, it must be considered also Airport and ATM fees. These are separate in landing C_{LND}, ground operation C_{GRND} and navigation fees C_{NAV}. The airport fees are function of total flight block time t_{block}, the Maximum Take-Off Weight (MTOW) and the payload N_{PL}. Ground operation includes the costs for the turn-around process of the aircraft and the passengers handling. While the navigation fees are charged from the ATM operators and relate to the range flown d_{range}, the MTOW and a navigation fee factor k_{nav} which depends on the type of flight [38]. The fees are evaluated as follows:

$$C_{FEES} = C_{LND} + C_{GRND} + C_{NAV} \tag{4.27}$$

where:

$$C_{LND} = MTOW \cdot N_{flight} \cdot (0.0095 - 0.001 \cdot ln(t_{block})) \tag{4.28}$$

$$C_{GRND} = N_{flight} \cdot (0.11 \cdot N_{PL} \; - \; 5 \cdot 10^{-7} \cdot N_{PL}^2) \tag{4.29}$$

$$C_{NAV} = N_{flight} \cdot \left(k_{nav} \cdot \frac{d_{range}}{1000} \cdot \sqrt{\frac{MTOW}{5000}} \right) \tag{4.30}$$

The block hours t_{block} measure the total time the aircraft is in use, from when the blockers are removed from the wheels at the departure airport to when they are placed on the wheels at the destination. Block hours, therefore, include taxi time, ground time, total mission flight time, airborne holding time, extra time for complying with air-traffic-control approach instruction, and time spent on the ground. In [64] can be found a way to compute the block hours, that is:

$$t_{block} = t_{gm} + t_c + t_{cr} + t_d + t_{am} \tag{4.31}$$

where

- t_{block} is the block time;
- t_{gm} is the ground maneuver time;
- t_c is the time spent in the climb;
- t_{cr} is the cruise time;
- t_d is the time spent in the descent;
- t_{am} is the time spent in air maneuvering.

These times can be determined analytically but there are different parameters which are not available in our case.

Depreciation

Specific depreciation costs $C_{ACdepre}$ as the first part of the indirect operating costs can be calculated as follows, considering the aircraft selling price P_{AC} and a linear depreciation, note that the battery depreciation has to be considered separately:

$$C_{ACdepre} = \frac{P_{AC}}{Q_{FLGT} \cdot h_{ops} \cdot t_{eol}} \tag{4.32}$$

The depreciation rate of the battery is derived with the life cycles of the batteries [45]:

$$C_{BATdepre} = \frac{C_{BAT} \cdot E_{bat}}{N_{BATc} \cdot d_{range}} \tag{4.33}$$

Insurance

Gudmundsson proposed insurance costs of:

$$C_{INS} = 500 + 15\% \cdot C_{ACin} \tag{4.34}$$

where:

- C_{ACin} is the insured valued of aircraft, considering a new design this amounts to the purchased price of the aircraft.

Capital expenditures

A CAPital EXpenditure (CAPEX) is the payment with either cash or credit to purchase goods or services that are capitalized on the balance sheet. To put it another way, it is any expenditure that is capitalized (i.e., not expensed directly on a company's income statement) and is considered to be an investment by a company in expanding its business. CAPEX is important for companies to grow and maintain their business by investing in new property, plant, equipment, products, and technology. According to [45] assuming a linear depreciation, the average CAPEX can be calculated as follows:

$$C_{CAPEX} = 0.5 \cdot WACC \cdot P_{AC} \tag{4.35}$$

Selling, general and administration

Selling, general and administrative expenses are a major non-production cost presented in an income statement. The SG&A costs C_{SGA} are considered with a surcharge factor on all the operator costs of F_{SGA}, which depends on the operator company (e.g., Lufthansa = 12% and American Airlines = 5% in the past five years). The operator costs comprise all previously listed cost items except for CAPEX:

$$C_{SGA} = F_{SGA} \cdot (C_{energy} \cdot C_{AM} \cdot C_{CREW} \cdot C_{FEES} \cdot C_{BATdepre} \cdot C_{ACdepre} \cdot C_{INS}) \tag{4.36}$$

The model described below could help the manufacturers to underline all those features which distinguish a hybrid-electric micro-feeder with respect to different competing aircraft design or competitive modes of transport.

Chapter 5

Conclusions

5.1 Outcomes

The aim of this work is to provide:

- a market study for evaluating the potential demand for a micro-feeder air transportation service;
- a procedure to evaluate the design and manufacturing costs of a hybrid-electric aircraft fleet fulfilling this role;
- a procedure to evaluate acquisition and operating costs of such fleet.

The candidate aircraft (in terms of load capacity, performance, energy requirements, etc.) is a user-specified input, while the number of airplanes to be produced derives from the market analysis. This is based on a general process that estimates the potential market for very short-haul flights within any European country, considering the candidate routes between minor airports and hubs.

Appropriate filtering methods allow selecting the routes that may actually compete with ground transportation means. According to a specific set of characteristics of the aircraft to be employed (8 passengers, 600 km maximum range), competitiveness of ground transportation means, and other reasonable assumptions, the candidate routes throughout Europe reduce from 124,256 to 401.

In this work, Germany, Italy and Estonia have been considered as case studies, being representative of three group of countries when it comes to their “transportation system efficiency", which is an index of ground transportation density. This index was defined based on the analysis of existing European ground transportation networks. From these data it comes out that three clusters can be defined according to the density indicator: countries which have a high, medium, and low transportation system efficiency. In this way, it is immediate to see where our service will be used as an optional mode to travel, with respect to the existing modes, just for convenience, and where it will be used as a primary mode of transportation due to the lack of an alternative.

In each case study, the corresponding candidate route network allows estimating a coverage area around every origin airport. In turn, this permits the definition of the annual potential market, through a model based on the value of annual passengers per nation. In Germany, considering a total population of 82,437,641, the potential users evaluated are 1,684,173. While in Italy 911,078 out of 61,219,113 are likely to use this service. Different considerations have been done for Estonia with 39,420 possible users, where the market is known by data. Indeed, the national scheduled flights operate all the possible routes in the country. However, they are operated by an 18-seater commuter twice a day 5 days of 7 and once a day in the weekend. These flights could be substituted by a micro-feeder which will reduce substantially the emission and the operational costs. This situation exists in different countries of this group. The annual potential market has been translated into the number of aircraft to be produced by an aircraft manufacturer company, which turns out to be 450.

The main contribution of the presented work can be summarized.

Cost analysis for design, manufacturing, and acquisition, is based on a modified version of the DAPCA (Development And Procurement Costs of Aircraft) method. The original formulation has been adapted to the General Aviation category, to better reflect the development and operational cost of a micro-feeder aircraft, and to the hybrid-electric configuration. The method establishes special cost estimating relationships that allow predicting the cost of engineering, tooling, manufacturing labor, and quality control; manufacturing material, development support, and flight testing; and total program cost. The major modifications to the current model are related to design, experience effectiveness (learning curve), changes in the price level of market basket of consumer goods and services purchased. The considerations needed for the design adjustments bring all the costs items to be classified into three categories:

- costs comparable to conventional aircraft;
- costs reshaped with respect to their conventional counterparts;
- costs defined ad-hoc for a hybrid-electric aircraft.

For the first costs, a design factor which takes into account the study of a micro-feeder is used. In the second step, a factor based on the degree of hybridization complement the design factor. While the final costs are evaluated by relying on existing cases. The cost is also adjusted using a special Quantity Discount Factor (QDF) to account the application of the experience effectiveness. According to the innovation of the project, it has been considered an experience effectiveness factor of 95%. The last adjustment to the model considers the cost of living in the year 2018 with respect to 2012, which involves a factor of 1.13. It comes out that the final cost per unit of the candidate hybrid-electric micro-feeder is 1,133,520€. Exploiting the NPV for the investment appraisal it turns out that the cash flow timing plays a relevant role in the cost analysis. Considering a price per unit of 1,473,570€, the investment results acceptable, since the NPV is positive. However, an improvement to the project could be done by considering a different type of payment, i.e. a certain percentage of anticipation by the customer.

Finally, a customized model is proposed to define an estimation procedure for the cost of operating a hybrid-electric micro-feeder. This results from the composition of different existing models. The primary inputs are flight hours per year, fuel cost, the acquisition cost of the aircraft, insurance costs, and some assumptions regarding the airline operating model. No application examples are provided within this work, as several of these input data are not sufficiently consolidated to derive reliable results.

All the described outcomes are sources of validated results from an external company that operates in this field. They derive from a new developed methodology. In order to bring us to these results, this work contributes to existing methods through new approaches. In particular:

1. it classifies all the EU countries through a mapping which is function of the ground transportation density index. This index is a combined index which considers all the existing transport networks and infrastructures. So far, this kind of classification is made analyzing which countries can afford a new service and not those that really need it. For this reason, our focus has shifted to the transportation system efficiency rather than an economical factor;

2. it develops a filtering procedure which allows selecting the routes of any kind of GA aircraft design according to a different set of inputs. It allows defining all those routes on which it is worthwhile inserting a new aircraft service or a different way to travel;

3. it implements a procedure that allows drawing maps, within which wherever a potential user is, it is more convenient to use the service provided rather than reaching the destination with another transport mode.

4. following the just mentioned mapping, a model to evaluate the potential users has been developed. Differently from the well known surveys used to evaluate the volume of potential users, this procedure estimates it starting from data on census and travelers of the mapped area;

5. it modifies an existing cost estimation model to reflect the usage of the candidate aircraft. Specifically, the model has been updated to estimate the manufacturer's and operator's costs of a hybrid-electric aircraft of the GA category.

5.2 Future developments

The present work represents a preliminary step towards the determination of a market scenario for the introduction of a hybrid-electric micro-feeder service in Europe's air transportation network. As such, many aspects that have been considered here may be improved and generalized, the main aim of the work being the setup of a methodology fit for this ambitious goal.

The procedure developed for demand estimation may be extended to include airfields (such as grassy airstrips), in addition to airports already included in the TEN-T network. This may provide a promising opportunity to boost air transportation, offering a highly distributed micro-feeder service, even in regions which are not endowed with minor airports. Indeed, the inclusion of airfields will add a wide network besides the comprehensive and core ones. Of course, point-to-point connections as well as air taxi services may profit from this extension. This may contribute to the habilitating means to get closer to the European target of extending the aviation market and improving personal mobility, allowing a higher percentage of travelers within Europe to be able to complete their journey, within 4 hours door-to-door.

In the future, an enhancement to this work could be provided by an accurate evaluation of the potential market of all the 28 EU Member States. This inevitably requires the availability of a higher computing power for the number-crunching operations performed on the considered databases.

Furthermore, in order to deliver reliable data for both manufacturer's and operator's cost estimation, an in-depth study is in order regarding aircraft manufacturer policies, procurement, and supply chain, as well as airline operating model and other operating cost elements.

Bibliography

[1] Zunum Aero. *Zunum Aircraft.* 2017. URL: https://zunum.aero/aircraft/.

[2] Siemens AG. *Aerobatic Airplane "Extra 330LE".* 2016.

[3] EEA - European Environment Agency. "Air Quality in Europe - Report 2016". In: *Air Quality in Europe* (2016).

[4] EEA - European Environment Agency. "Noise in Europe - Report No10/2014". In: *EEA Report No 10/2014, European Environment Agency* (2014).

[5] Diamond Aircraft. *About Diamond - Innovation.* 2017. URL: https://www.diamondaircraft.com/about-diamond/innovation/.

[6] Marıa Isabel Blanco. "The economics of wind energy". In: *Renewable and sustainable energy reviews* 13.6-7 (2009), pp. 1372–1382.

[7] Marty K Bradley and Christopher K Droney. "Subsonic Ultra Green Aircraft Research: Phase 2. Volume 2; Hybrid Electric Design Exploration". In: (2015).

[8] Benjamin J Brelje and Joaquim RRA Martins. "Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts, models, and design approaches". In: *Progress in Aerospace Sciences* (2018).

[9] Federal Office of Civil Aviation (FOCA). "ICAO Action Plan on CO_2 Emission Reduction". In: *Federal Department of the Environment, Transport, Energy and Communications DETEC Federal Office of Civil Aviation FOCA* (2015).

[10] Sean Clarke et al. "X-57 power and command system design". In: (2017).

[11] European Commission. *Air transport traffic data by airports, aircraft and airlines.* 2018. URL: https://ec.europa.eu/eurostat/data/database.

[12] European Commission. "Building the Transport Core Network: Core Network Corridors and Connecting Europe Facility". In: *The planning methodology for the trans-European transport network (TEN-T)* (2014).

[13] European Commission. *Infrastructure - TEN-T - Connecting Europe.* 2018. URL: https://ec.europa.eu/transport/themes/infrastructure/ten-t-guidelines/maps_it.

[14] European Commission. *Population census*. 2018. URL: `https://ec.europa.eu/eurostat/data/database`.

[15] European Commission. *Railway transport infrastructure*. 2018. URL: `https://ec.europa.eu/eurostat/web/transport/data/database`.

[16] European Commission. *Road transport infrastructure*. 2018. URL: `https://ec.europa.eu/eurostat/web/transport/data/database`.

[17] European Commission. *TENtec Interactive Map Viewer*. 2018. URL: `http://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html`.

[18] XTI Aircraft Company. *XTI TriFan 600*. 2017. URL: `http://www.xtiaircraft.com/trifan-600/`.

[19] Electric Aircraft Corporation. *Electric Aircraft Corporation: Home of the ElectraFlyer*. 2018. URL: `http://www.electraflyer.com/`.

[20] Michael R Dudley et al. "Second Annual Transformative Vertical Flight Concepts Workshop: Enabling New Flight Concepts Through Novel Propulsion and Energy Architectures". In: (2015).

[21] EASA. *Certification specifications for normal, utility, aerobatic, and commuter category aeroplanes CS-23*. 2003.

[22] EASA. *European Aviation Environmental Report*. 2016. URL: `https://www.easa.europa.eu/eaer/topics/overview-aviation-sector/figures-and-tables`.

[23] Charles N Eastlake and Harry W Blackwell. "Cost Estimating Software for General Aviation Aircraft Design". In: *age* (2000).

[24] EEA, EASA, and EUROCONTROL. "European Aviation Environmental Report 2016". In: *European Aviation Environmental Report EAER* (2016).

[25] EUROCONTROL. *IMPACT web application*. 2018. URL: `https://www.eurocontrol.int/articles/impact`.

[26] EUROCONTROL. *SysTem for AirPort noise Exposure Studies (STAPES)*. 2018. URL: `https://www.eurocontrol.int/services/system-airport-noise-exposure-studies-stapes`.

[27] EUROSTAT. *Data on taxation*. 2018. URL: `https://ec.europa.eu/taxation_customs/business/economic-analysis-taxation/data-taxation_en`.

[28] Eviation. *Alice Commuter - Eviation*. 2018. URL: `https://www.eviation.co/alice/`.

[29] Yann Fefermann et al. “Hybrid-Electric motive power systems for commuter transport applications”. In: *Proceedings of the 30th Congress of the International Council of the Aeronautical Sciences, Daejeon, Korea.* 2016, pp. 25–30.

[30] James L Felder. “NASA electric propulsion system studies”. In: (2015).

[31] C Friedrich and P A Robertson. “Hybrid-electric propulsion for aircraft”. In: *Journal of Aircraft* 52.1 (2014), pp. 176–189.

[32] Emma Frosina et al. “Modelling of a Hybrid-Electric Light Aircraft”. In: *Energy Procedia* 126 (2017), pp. 1155–1162.

[33] Airbus Group. *E-Fan: The New Way to Fly.* 2018. URL: `http://company.airbus.com/service/mediacenter/download/?uuid=48b1bd2c-a428-4c65-82e5-ed3e923bd142`.

[34] Airbus Group and Rolls Royce. *Airbus and Rolls Royce E-Thrust.* 2017. URL: `https://www.airbus.com/innovation/The-future-is-electric.html`.

[35] Snorri Gudmundsson. *General aviation aircraft design: Applied Methods and Procedures.* Butterworth-Heinemann, 2013.

[36] *GuruFocus.* 2018. URL: `https://www.gurufocus.com/`.

[37] Markus Hagen et al. “Lithium–Sulfur Cells: The Gap between the State-of-the-Art and the Requirements for High Energy Battery Cells”. In: *Advanced Energy Materials* 5.16 (2015), p. 1401986.

[38] Julian Hoelzen et al. “Conceptual design of operation strategies for hybrid electric aircraft”. In: *Energies* 11.1 (2018), p. 217.

[39] ICAO. “Aircraft CO_2 emission standard metric system”. In: *ICAO Fact Sheet AN1/17* (2013).

[40] Askin T Isikveren et al. “Conceptual studies of universally-electric systems architectures suitable for transport aircraft”. In: (2012).

[41] Askin T Isikveren et al. “Optimization of Commercial Aircraft Using Battery-Based Voltaic-Joule/Brayton Propulsion”. In: *Journal of Aircraft* (2016), pp. 246–261.

[42] Amy Jankovsky, Cheryl Bowman, and Ralph Jansen. “Building Blocks for Transport-Class Hybrid and Turboelectric Vehicles”. In: (2016).

[43] S Kallas et al. “Flightpath 2050 Europe’s Vision for Aviation”. In: *Report of the High Level Group on Aviation Research, European Commission, Brussels, Belgium, Report No. EUR* 98 (2011).

[44] Robert Kochhan et al. “An overview of costs for vehicle components, fuels and greenhouse gas emissions”. In: *researchgate. net* (2014).

[45] M Kreimeier et al. “Economic Assessment of Air Mobility On-Demand Concepts”. In: *Journal of Air Transportation* 26.1 (2018), pp. 23–36.

[46] Bureau of Labor Statistics. “Labor force statistics from the current population survey”. In: (2015).

[47] Jack W Langelaan et al. “Green flight challenge: aircraft design and flight planning for extreme fuel efficiency”. In: *Journal of Aircraft* 50.3 (2013), pp. 832–846.

[48] Nieves Lapeña-Rey et al. “First fuel-cell manned aircraft”. In: *Journal of aircraft* 47.6 (2010), pp. 1825–1835.

[49] Ankit Nanda. “The propulsive design aspects on the world’s first direct drive hybrid airplane”. In: (2011).

[50] Decision No. “1692/96/EC of the European Parliament and of the Council of 23 July 1996 on Community guidelines for the development of the trans-European transport network”. In: *GU L* 228.9 (1996), p. 11.

[51] European Parliament and European Council. “Directive 2002/49/EC”. In: *Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise* (2002), pp. 473–482.

[52] European Parliament and European Council. “Regulation 598/2014”. In: *Regulation 598/2014 of the European Parliament and the Council of 16 April 2014 on the establishment of rules and procedures with regard to the introduction of noise related operating restrictions at Union airports within a Balanced Approach and repealing Directive 2002/30/EC* (2014), pp. 65–78.

[53] Brian Pearce. “Profitability and the air transport value chain”. In: *IATA Economics Briefing* 10 (2013).

[54] Pipistrel. *Alpha Electro Technical Data.* 2014. URL: `https://www.pipistrel.si/plane/alpha-electro/technical-data`.

[55] Pipistrel. *Taurus Electro G2 Technical Data.* 2014. URL: `http://www.pipistrel.si/plane/taurus-electro/technical-data`.

[56] Pipistrel and T A Horne. *Pipistrel Alpha Electro: The Trainer of the Future?* 2015. URL: `https://www.aopa.org/news-and-media/all-news/2015/october/pilot/f_pipistrel/`.

[57] C Pornet et al. *Methodology for sizing and performance assessment of hybrid energy aircraft.* 2013.

[58] Flight Radar. *Air transport traffic data in Estonia.* 2018. URL: `https://www.flightradar24.com/data/airports/estonia`.

[59] Carlo E D Riboldi and Federico Gualdoni. "An integrated approach to the preliminary weight sizing of small electric aircraft". In: *Aerospace Science and Technology* 58 (2016), pp. 134–149.

[60] Tim Richardson. "The Trans-European transport network: environmental policy integration in the European Union". In: *European Urban and Regional Studies* 4.4 (1997), pp. 333–346.

[61] Niccolò Rossi. "Conceptual design of hybrid-electric aircraft". In: (2018).

[62] Ned Schiff and Rich Schiferl. *Latest Developments in Superconducting Motors.* 2000. URL: `https://www.machinedesign.com/motorsdrives/latest-developments-superconducting-motors`.

[63] Benjamin T Schiltgen and Jeffrey Freeman. "Aeropropulsive interaction and thermal system integration within the ECO-150: a turboelectric distributed propulsion airliner with conventional electric machines". In: *16th AIAA Aviation Technology, Integration, and Operations Conference.* 2016, p. 4064.

[64] Pasquale M Sforza. *Commercial airplane design principles.* Elsevier, 2014.

[65] Republic of Slovenia MINISTRY OF FINANCE. *Tax regulations in Slovenia.* 2018. URL: `http://eugo.gov.si/en/running/taxes/`.

[66] Stefan Stückl, Jan van Toor, and Hans Lobentanzer. "VOLTAIR–the all electric propulsion concept platform–a vision for atmospheric friendly flight". In: *28th International Congress of the Aeronautical Sciences (ICAS).* 2012.

[67] H J Sung et al. *A study on the required performance of a 2G HTS wire for HTS wind power generators.* 2016.

[68] Egbert Torenbeek. *Advanced aircraft design: conceptual design, analysis and optimization of subsonic civil airplanes.* John Wiley & Sons, 2013.

[69] DC United States Department of Labor Washington. *CPI Inflation Calculator.* 2018. URL: `https://www.bls.gov/data/inflation_calculator.htm`.

[70] Glen Van Brummelen. *Heavenly mathematics: The forgotten art of spherical trigonometry.* Princeton University Press, 2012.

[71] Jason Welstead et al. "Overview of the NASA STARC-ABL (Rev. B) Advanced Concept". In: (2017).