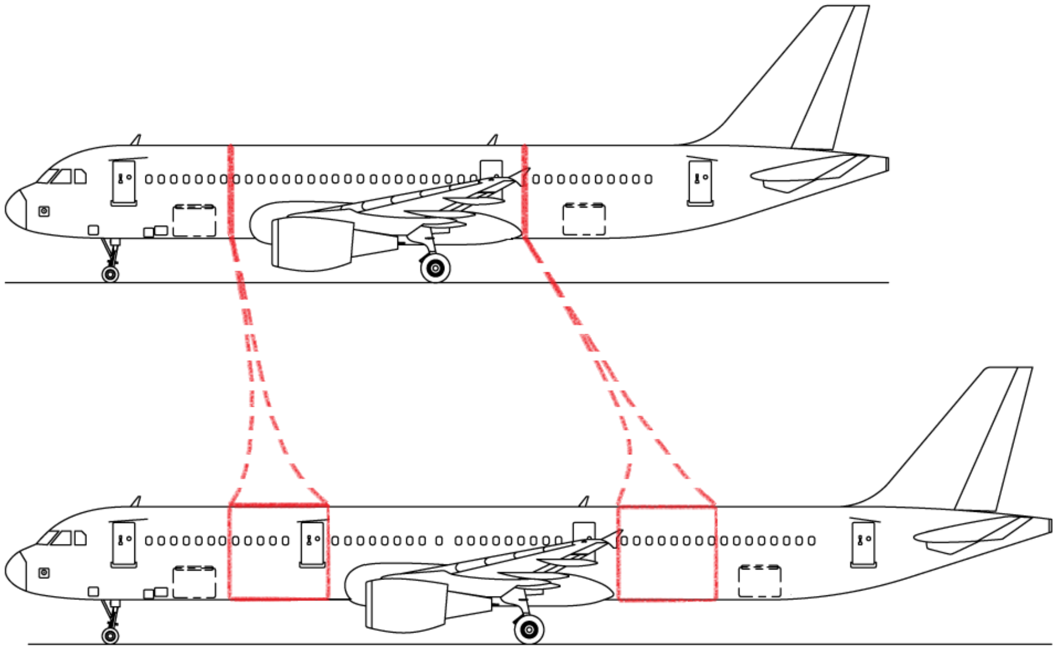
Design of a modular fuselage for commercial aircraft

To cope with seasonal variation in passenger demand

Q.P.D. van Keymeulen

Master of Science Thesis



Delft University of Technology

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September 27, 2015

Faculty of Aerospace Engineering · Delft University of Technology

TU Delft Delft University of Technology

DELFT UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF
AERODYNAMICS, WIND ENERGY, FLIGHT PERFORMANCE &
PROPULSION (AWEP)

The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled

DESIGN OF A MODULAR FUSELAGE FOR COMMERCIAL AIRCRAFT

by

Q.P.D. VAN KEYMEULEN

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE AEROSPACE ENGINEERING

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Chairman: Dr. Arvind Gangoli Rao

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Abstract

The subject of this research is a new concept of modular aircraft designed to cope with the seasonal variation in passenger demand by opening the fuselage and increasing its length with extra bits of fuselages. The goal is to find out if this new aircraft concept is more profitable than the current alternatives. Previous work have looked at increasing the size of existing aircraft only once in their lifetime. Or offered opening mechanisms for jet fighters or studied modularity for products or Unmanned Aerial Vehicles (UAV). The idea is to design a new aircraft from scratch able to change its size twice a year in order to improve the offer to the passenger demand.

The research was performed in four phases by making two tools. The first phase is making the first tool which allows the design of a family of aircraft according to an input network and passenger demand. This is going to serve as basis of comparison for the modular aircraft. The second phase is making the second tool, based on The Initiator, able to design a modular aircraft. The third phase is performing a structural analysis to compute the mass penalty caused by the connection mechanism. The final phase is studying the profitability of the modular aircraft compared to the optimal family form the first phase. This economical study is performed at two levels: the aircraft level and the airline level.

The best concept is starting with the long version. Then the short version uses the same wing and tail but smaller engines and landing gear. When using a safety factor of 8 for the connection mechanism, the mass penalty is relatively small ranging from 1 to 6% of the fuselage mass depending on the aircraft configuration. The principal factor driving the performance of the modular aircraft is not the mass penalty but the non-optimal wing used for the short version. To generate the same profitability as the optimal design, the modular aircraft should reach a load factor of 85.6% instead of 80%. Even in a network, the increased fit between the offer and demand cannot outweigh the design penalty.

As a result, the potential for a modular aircraft seems low when compared to the alternatives able to increase the aircraft utilization such as real-time-health monitoring of aircraft to improve the maintenance and price-setting algorithms able to improve both the load factor and the profitability.

Acknowledgements

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Brussels, Belgium
August 13, 2015

Quentin Van Keymeulen

Table of Contents

Glossary

List of Latin Symbols

Alt_{cruise} Cruise altitude $[m]$

$C_{L_{max}}$ Maximum Lift coefficient

d_{land} Landing distance $[m]$

d_{T-O} Take-Off distance $[m]$

M_{cruise} Cruise Mach Number $[-]$

List of Greek Symbols

$\aleph$ Set of all natural numbers including 0 (0, 1, 2, 3,...)$[-]$

$\Re$ Set of all real numbers $[-]$

Acronyms

ACARE Advisory Council for Aeronautics Research in Europe

ASK Available Seat Kilometer

CAD Computer Aided Design
CASK Cost per Available Seat Kilometer

DEE Design and Engineering Engine solution
DLM Design Landing Mass [kg]
DOC Direct Operating Costs

ESA European Space Agency

FE Finite Elements

IATA International Air Transport Association
ICAO International Civil Aviation Organization
IOC Indirect Operating Costs

KBE Knowledge Based Engineering

LCC Life Cycle Cost

MDO Multi-disciplinary Design Optimization
MIP Mixed Integer Programming
MNT Maximum Number of different aircraft Types
MTOM Maximum Take-Off Mass [kg]

NASA National Aeronautics & Space Administration
NRC Non-Recurring Costs

OEM Operating Empty Mass [kg]
OwC Cost of Ownership

RPK Revenue Passenger Kilometers

TOC Total Operating Costs

ZFM Zero Fuel Mass [kg]

Chapter 1

Introduction

1-1 Global context

The long standing 5% growth rate per year in air traffic demand (measured in Revenue Passenger Kilometers (RPK)) is expected to continue for the next 20 years[1]. Limiting the environmental impact of aviation is clearly going to be a challenge for the aircraft manufacturers and airlines. In order to secure Europe's global competitiveness and to address this challenge, the European Commission has launched its biggest ever research an innovation program called Horizon 2020 with a budget of nearly €80 billion of funding available over 7 years (2014 - 2020) for many different area, including air transportation. Close to €2 billion are allocated to the Clean Sky 2 program which is planned to run from 2014 to 2023. It will build on the success of Clean Sky to deliver full-scale in-flight demonstration of novel aircraft configurations, systems/propulsion architectures and make important strides towards the new goals of the Advisory Council for Aeronautics Research in Europe (ACARE)'s Flightpath 2050. Amongst other goals, ACARE aims at reaching by the year 2020 a 50% reduction in CO_2 emissions and a 75% reduction by year 2050 (relative to typical new aircraft in 2000)[2]. In America, authorities set goals on decreasing environmental impact as well. The International Civil Aviation Organization (ICAO) has set the main objective of achieving at least 2% fleet-wise reductions in CO_2 emissions for aviation through 2050 [3]. The International Air Transport Association (IATA)'s goal is a reduction in net emissions of 50% below 2005 levels by 2050[4].

1-2 Seasonal traffic variation

To be profitable, airlines require a high intensity of operation. This is why the important seasonal variation in passenger traffic is a crucial problem. The effect is well documented and figure 1-1 shows 2 years of international traffic starting in July 2012 according to IATA's monthly report. As it can be seen, there is an important variation between the quietest month, February, and the busiest months of July and August. The seasonal variation can be computed between the quietest month ($252{\cdot}10^9 RPKs$, February 2013) and the busiest month ($360{\cdot}10^9 RPKs$, August 2013) compared to the average of the year 2013: $304{\cdot}10^9 RPKs$. So the lowest month has 17% less traffic than average and the highest month 18% more. This results in a variation of 35% maximum.

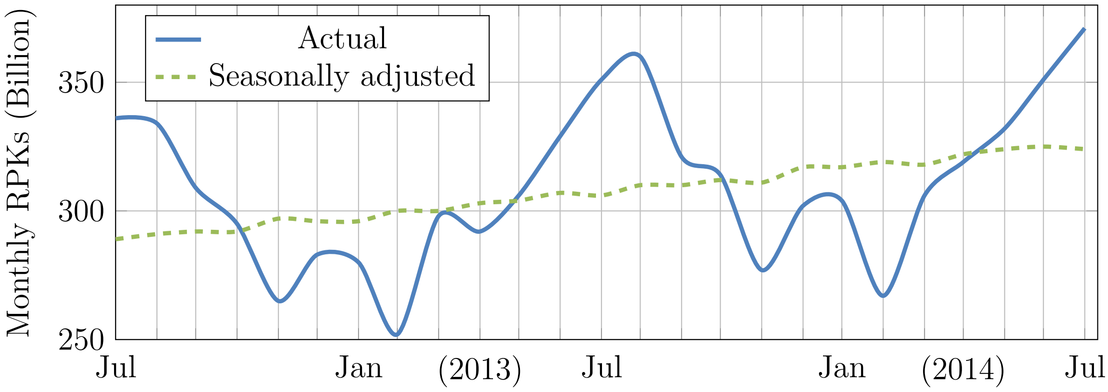

Figure 1-1: July 2012 to July 2014 International Passenger Market [5]

The load factor airlines have managed to reach in 2013 is 79.5% [6]. It is a historical record high but there is still room for improvement. One way of improving the load factor is by using modular aircraft, which is the subject of this report.

1-3 Aircraft manufacturer's context

Next to the forecast growth of the market and the need to decrease emissions, there is also an emphasis in the aerospace industry to move from the initial "higher, faster, farther" era to the "better, faster, cheaper" era. This means that the goal is to decrease the total life-cycle cost of aircraft while keeping good performances. This in turn, translates to aircraft manufacturers being more conservative in taking risks and privileging incremental innovations instead of radical ones.

Indeed, the 787 caused headaches for Boeing and the program is still cash-flow negative. So rather than betting the company with revolutionary technology, aerospace firms are increasingly changing their approach. The new product strategy aims to develop future programs in incremental steps, rather than the more risky alternative: "moon-shots"[7]. According to Boeing's ex-CEO Jim McNerney, the focus of the aircraft manufacturers should be on replicating systems and technologies already proven and paid for. The vision is sensibly the same at Airbus. As a result, the more attractive options are to re-engineer familiar platforms and harvest new technology to deliver programs like the A320neo and the 737MAX.

The consequence of this conservative approach is that there are less new programs launched by aircraft manufacturers. The first new program scheduled is by 2030, to replace the A320neo and 737MAX. Even those programs are going to be conservative [8].

A modular aircraft, as investigated in this research, has a fuselage that can be opened to add sections in order to increase its passenger capacity. Varying the size of the fuselage would take place twice a year to follow the seasons, or a few time over the course of the aircraft's life to adapt to the market.

The concept of having a modular fuselage is in line with this reduction in risk-taking strategy. In addition it offers more flexibility to the airlines that have to make long-term investments in aircraft without knowing the traffic demand and competition state in the future.

1-4 Thesis Goal and Research Question

1-4-1 Research question

The need for more cost-effective and more sustainable aircraft together with the seasonal variation of passenger leads to the following research question:

> *Are modular aircraft with extensible fuselage, within a family, feasible and more cost-effective than current aircraft designs to cope with seasonal varying passenger demand?*

The following sub-questions have been established to answer the research question:

- How to design an optimal aircraft family?
- Can a modular fuselage section provide a 35% capacity change, and if not, what would be required to make it possible?
- What is the weight penalty for the connection mechanisms?
- Where should the section(s) be added? (front, middle or rear of the fuselage)
- What are the performance improvements (measured in profits for the airline) compared to non-modular aircraft for seasonally varying passenger demand? (if any)
- Is changing the engines and landing gear between configurations while keeping the wing and tail constant a good approach?

1-4-2 Thesis goals

In order to answer the research question and the sub-questions, the thesis has the two following goals:

> *Develop an optimization tool to design an aircraft family for a specific network of routes and demand. Analyze the flight and economics performance of an aircraft with extensible fuselage and varying engines and landing gear using the Initiator design tool.*

The analysis in this thesis is limited to the conceptual design phase of aircraft design.

1-4-3 Thesis Outline

Chapter 2 presents background information in 3 sections: first the state of the air in aircraft family design is presented. Then basic aircraft economics are presented followed by the methodology and limitations of this research.

Chapter 3 presents the modular aircraft concept.

The first of the two tools created for this research is presented in chapter 4. It describes the family design tool that serves as basis for the evaluation of the modular fuselage concept.

The second tool is presented in chapter 5 where the Initiator design tool is modified to analyze the new aircraft concept.

Chapter 6 analyses the structural loads acting on the fuselage, it sizes the connection mechanism to estimate the mass penalty.

Chapter 7 analyses the flight performance and profitability on two cases: the first one is at the aircraft level and the second one at the airline level.

Chapter 8 presents the conclusions and recommendations that follow from this thesis on the potential of the modular fuselage concept.

Chapter 2

Background

Thie chapter is divided in three. Section 2-1 presents aircraft family design. Then, section 2-2 presents basic aircraft economics aspects such as cost breakdown and other concepts relative to the economic evaluation of a new aircraft concept. Finally, section 2-3 explains the methods and limitation of this research.

2-1 State of the art in aircraft family design

This section is divided in three parts, first definitions are presented. Then work concerning general product family design and design for flexibility is discussed. Finally the core subject is examined: aircraft family design.

2-1-1 Definitions

Three important terms in the context of aircraft design are defined hereunder:

Flexibility: Ready and able to change so as to adapt to different circumstances [9].

Modular: A modular system has parts that can be connected or combined in different ways[10].

Reconfigurability: A reconfigurable system is one which the geometry or composition can be changed repeatedly and reversibly during the operational lifespan of the system. It enables three primary capabilities: ability to perform multiple functions non-concurrently, increased system survivability and ability to evolve over time. This definition comes from Ferguson et al.(2007) [11] and is more specific to this thesis.

Flexibility in system design should address the following questions[12, 13]:

- What is flexibility?
- Why or when is flexibility needed in system design?
- How can flexibility be taken into account in the design? What are the design principles for embedding flexibility in system design?
- What are the trade-offs associated with designing for flexibility? What is the value of flexibility and what are the penalties (cost, performance, risk, etc.), associated with it?

These questions are going to be answered in this thesis.

The major reason for the development of a reconfigurable aircraft is the seasonal variation in passenger demand, corresponding to Fricke and Schulz's *"significant variation in anticipated operating environments"* [14].

2-1-2 Product family design & design for flexibility

In Simpson's context[15, 16], the modularity occurs at the time of design and not during the use of the product. There are two types of product families[15, 17]: one is based on a baseline product stretched or shrunk, as is the case for this research; the other is based on modular components.

Alizon et al.[18] describe four design processes for product family design based on two different approaches: top-down and bottom-up and two drivers: product-driven or platform-driven. This is illustrated in figure 2-1 on page 7.

The modular aircraft is in the "Top-Down, Platform-driven" category. It falls in the "Top-Down" section because there are no pre-existing products on which the family has to be based. The disadvantage is that the design process begins with customer needs which is riskier. But the advantage is that starting from a blanc page gives more design freedom. Then it is "Platform-driven" because all the products (in this case both the long and short versions of the aircraft) are designed at once. The platform is defined at the functionality level (as opposed to the customer needs level). The advantage of a "platform-driven" family design process is that the resulting product family is more efficient, which is very important in the aircraft industry. But the two main disadvantages are: increased time to market and need for lots of time and resources to develop the platform.

The major objective of flexible design is finding the combination of adaptable and robust variables that give the desired flexibility for maximum profit[19]. Naturally, the cost

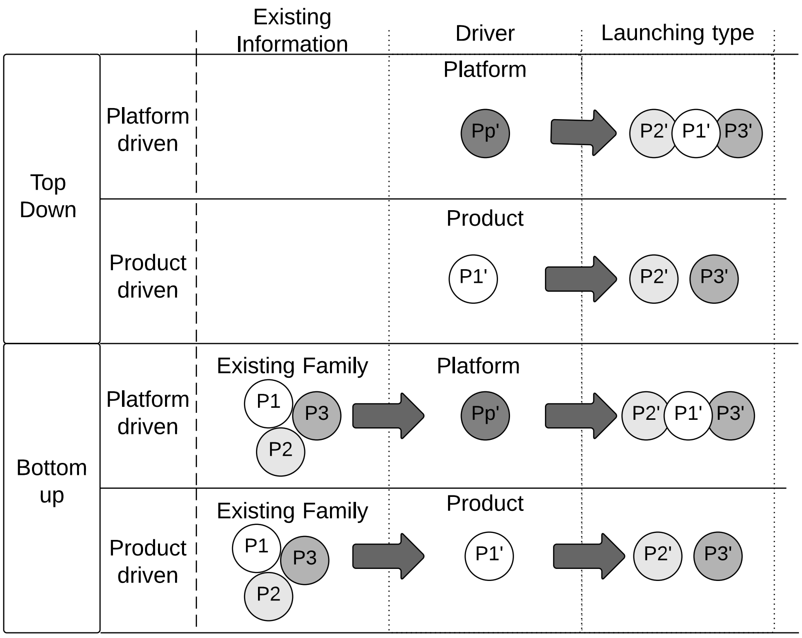

Figure 2-1: Different types of product family design processes

of flexible design system should be outweighed by its benefits[20, 21, 22].

To conclude this section, these researchers are interesting and provide methodologies to be used. The degree of modularity (modular fuselage/wing/tail/engine,...) is a variable. But it would be better to limit it to the fuselage or maybe the tail. The reason is because it is already complicated enough to just change the length of the fuselage in a short time-span. Indeed, the absolute maximum is five days[1]. For a comparison, an engine is fastened to the aircraft with a few bolts. Because of the small tolerances, only changing an engine can take up to one day because of the difficulty to align it properly to fasten it.

2-1-3 Aircraft family design

Originally, what has been done in the past is design a family of aircraft based on one model that is optimized and then variants are designed around it for slightly more or less payload or range[23]. This allows to meet different market needs and the commonality of the structural elements in the family can improve flexibility and secure cost savings.

But this traditional approach to family aircraft design of modifying one optimized aircraft

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[1] source: interviews with airlines

can lead to many modifications resulting in a practically new aircraft with sub-optimal performances according to Willcox and Wakayama[24]. Furthermore, they indicate that a reduction in cost is achievable by conceiving a family of aircraft that share common parts (such as planform and systems) but each aircraft satisfies a different mission requirement. Similarly, D'Souza ans Simpson[25] examine product family optimization for general aviation aircraft and Funk et al. describe the design of a family of large common military aircraft[26].

So a more recent approach is to design aircraft families from the start. Common components can lead to a significant reduction in the manufacturing cost (by lowering development, tooling and assembly costs) and some reduction in the direct operating costs (by simplifying fleet maintenance, lowering the spare parts inventories and training costs. But the lower manufacturing cost comes at a price of structural weight penalty compared to individually optimized aircraft[27].

One way to reduce costs and improve performance is to account for the utilization of the aircraft already in the design phase, more particularly making sure the aircraft's range is fully utilized once in operation. According to Yutko[28], the mean utilization range (average distance flown per flight) of narrow-body aircraft in the US in 2006 was 41% of the range. According to interviews performed with airlines in Amsterdam and Brussels, there is a similar concern in Europe concerning the fit of the aircraft's range to the allocated route. Taylor and de Weck studied the concurrent optimization of an aircraft coupled to a network[29]. Optimizing the aircraft design and the transport network improves operational efficiency and reduces the operational cost of the network. These results were confirmed by Mane and Crossley who even extended the research to incorporate uncertain passenger demand[30, 31].

Two patents displayed in appendix A on page 77 are also interesting and the first one [32] comes close to the subject of this thesis. The idea is to make a larger aircraft by reusing already existing aircraft like the 747 and adding a section and a set of wings as sown in figure A-1a. The second patent[33] concerns a modular connection device for an airplane body. But it is inconvenient to let passengers through as shown in figure A-1b.

To summarize previous work in this section, there are two important topics, the first one is family design for aircraft and the second one is optimal range utilization. The family design evolved from a simple optimized aircraft that was stretched or shrunk, then families are designed from the start and finally the design incorporates also the routes and passenger demand to account for optimal range utilization.

2-1-4 Existing aircraft family design tools

The context of an aircraft family design tool is to be able to enter requirements for different aircraft, then the software decides of the best way to combine them to obtain a predefined number of aircraft belonging to the same family. Many softwares are capable of designing an aircraft, as can be seen by the existing softwares described in chapter 5. However, after extensive researches no softwares capable of designing families of aircraft were found.

2-2 Aircraft economics

The field of aircraft economics and cost estimation includes many different disciplines and is complex. As a result, the scope of this background information chapter about aircraft economics is limited to the following three topics. Sub-section 2-2-1 presents the concept of Life Cycle Cost (LCC). Sub-section 2-2-2 presents an overview of 12 different cost estimation techniques available plus a tool to select the most suitable one and the available softwares. Finally, sub-section 2-2-3 presents economics aspects related to manufacturing and operating aircraft such as cost-breakdown structure.

2-2-1 The Life Cycle Cost in the Aerospace Industry

The particularity of LCC is that the complete life of the aircraft is considered: from design to disposal [34]. Marx, Marvis and Schrage give the following definition of LCC in their paper [35]:

> *"The process of building abstractions or models of the three primary components of the system life cycle for the purpose of gaining insight into the interactions between these components, and their mutual interactions and interdependencies with the manufacturer and the airlines."*

Where the three components from this definition are the non-recurring cost, the recurring costs and the operations & support costs.

According to Asiedu, LCC is also called concurrent engineering [36]. The segmentation of a the life cycle of a product varies in the literature. But according to Asiedu, the most common segmentation and cost-breakdown of LCC found in the literature is given in figure 2-2. The LCC is widely used in the literature and the industry since it is important in developing and buying affordable aircraft.

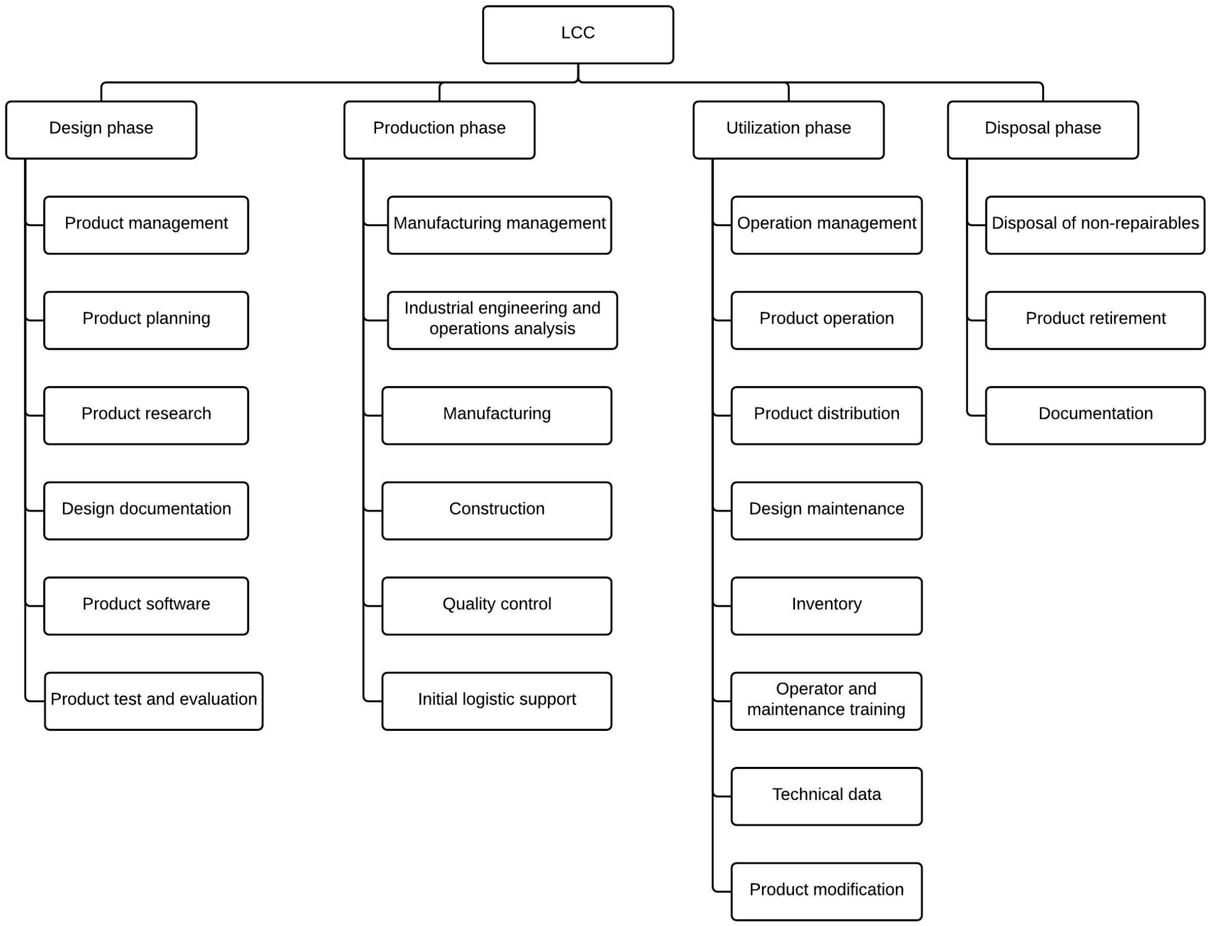


Figure 2-2: LCC segmentation and cost-breakdown according to Asiedu [36]

2-2-2 Overview of cost estimating methods

When designing a new aircraft concept, estimating its cost is very important. It enables to evaluate the interest of the aircraft and if it is worth producing or buying. However it is difficult since it requires a lot of information and knowledge. This sub-section presents the classification done by Niazi et al. because it is particularly complete, then the 12 techniques are described followed by table 2-1 presenting their pros and cons .

Figure 2-3 presents the classification of twelve different techniques according to Niazi et al. Qualitative techniques compare the new product to existing products. They are used in the conceptual design phase. Quantitative techniques require more information on the product, its design, features and manufacturing processes. This information is fed in analytical functions or other tools to determine the cost according to the components, the resources required and the processes used. Intuitive techniques rely on past production experience from knowledge experts.

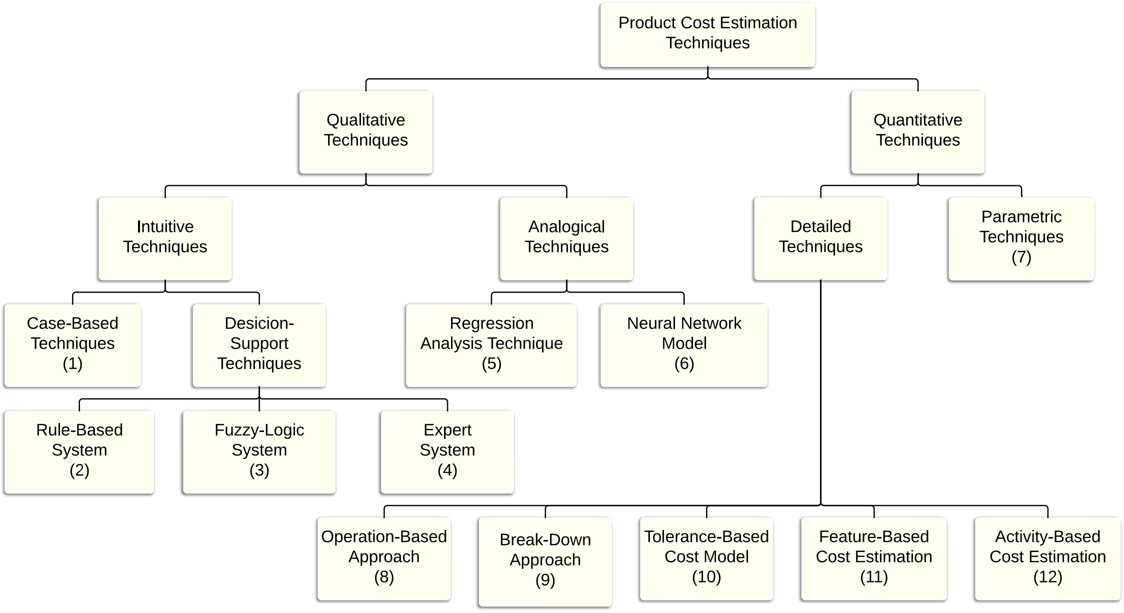


Figure 2-3: Classification of cost estimation techniques according to Niazi et al.[37]

1. Case-based methods use costs stored in databases from similar past products as a basis. The relevant changes are performed to give a cost estimate.
The other category falling under the intuitive techniques is the decision support techniques. This tool provides both a cost estimation and help in evaluation design alternatives. There are three types of estimation techniques presented hereunder (method 2 to 4):
2. Rule-based techniques calculate the cost according to the process used and the required time.
3. Fuzzy-logic methods date back to the middle of the XX^{th} century when it was introduced to deal objectively with uncertainty and precision. It uses a series of if-then rules while allowing the variables to belong to multiple fuzzy sets.
4. Expert system use expert knowledge stored in databases. One of the first applications of expert systems was MYCIM developed in the 70's at Stanford to perform medical diagnosis[38] and written in Lisp. When used in the Computer Aided Design (CAD) context it is called Knowledge Based Engineering (KBE).
Analogical techniques also use cost estimation of past products. But instead of relying on expert knowledge, it is based on actual data. There are two techniques presented hereunder:
5. Regression analysis works using the correlation between the cost of past projects and design variables. To be reliable it requires large sets of data and good correlation between the variable(s) and the cost.
6. Neural network simulate the human thought process and are able to learn from a

large database from historic projects
Now moving to the quantitative part of the classification. The first technique is:
7. Parametric technique, is called a "top-down" approach[36]. It uses cost-drivers parameters such as weight, complexity and performance to determine cost together with historic data and some form of regression analysis to analyze the relationship between the parameters and the cost.
The other quantitative approaches are grouped under the detailed techniques. They are "bottum-up" as their basis for estimating the costs are labor time and rates plus material quantities and price. These approaches are best suited for identical products with long and stable productions [39]. These methods are particularly accurate but also the most time consuming. They are the last five presented hereunder:
8. Operation-based. This technique allows an estimation of the manufacturing cost only. It can only be used in the detailed design phase to evaluate different production processes..
9. Break-down is quite easy but also only determines the production cost.
10. Tolerance-based. This method uses the tolerances assigned to the parts to determine a product cost estimation.
11. Feature-based modeling uses the design-features as cost driver. Since the more features a product has, the more expensive it is over its life cycle[40]. This approach is liked in the industry but not much used since it requires more research to confirm its feasibility.
12. Activity Based Costing (ABC) is based on the cost of the activities required to manufacture a product.

Niazi et al. also present a method to select a cost estimation technique summarized in figure 2-4. According to this, the best tool to be used in the conceptual design phase is the analogy method and the second best tool is the parametric method.

The two most popular softwares to estimate costs in the aerospace industry are PRICE and Galorath. PRICE is used for instance by the European Space Agency (ESA) [36], National Aeronautics & Space Administration (NASA) [42], Lockheed Martin and British Aerospace [43]; while according to Galorath's website, is used for instance by Airbus, Boeing, Raytheon, Rockwell Automation and Northrop Grumman. The Initiator design tool also has a cost estimation model included in it.

2-2-3 Engineering economics

The following two sub-sections present cost breakdown for both the aircraft manufacturers and the operators (usually airlines and lease companies, but they can also be private companies and individuals).

Ref	Name	Pros	Cons
1	Case-Based	Fast technique. Useful for conceptual & innovative design.	Available data is limited.
2	Rule-Based System	Includes sanity check by user. Expert knowledge is stored in design rules. Can provide optimized results.	Can be time consuming proportional to the amount of processes.
3	Fuzzy-Logic System	Deals with imprecision and uncertainty.	Technique is not well established.
4	Expert-System	Incorporates expert knowledge. Faster, more consistent and accurate results.	Limited by the amount expert knowledge can be stored. Complex programming required.
5	Regression Analysis	Simple technique.	Limited by data.
6	Neural Network	The system trains it self. Rather precise estimates. Deals with uncertainty and non-linear problems.	Highly data dependent. Not applicable to innovative designs. Lacks transparency.
7	Parametric	Fast technique, requires little product information. Useful for early stage estimating. Easy technique that requires little estimating skills.	Limited by ability to identify cost drivers. Requires large data set.
8	Operation-Based	Allows evaluation of production processes.	Not useful for early design trade-off. Requires detailed design information and process planning. Time consuming.
9	Break-Down	Easy technique.	Requires knowledge on purchasing, processing and maintenance.
10	Tolerance-Based	Tolerances identify complexities.	Requires detailed design information. Assigning correct tolerances is difficult.
11	Feature-Based	Features with high costs can be identified.	Allocating parts or properties to features can be difficult for small and complex products.
12	Activity-Based	Easy and effective technique using unit activity costs.	Requires lead times in early design stages.

Table 2-1: Pros and cons of cost estimating techniques [41] as defined in figure 2-3 (page 11)

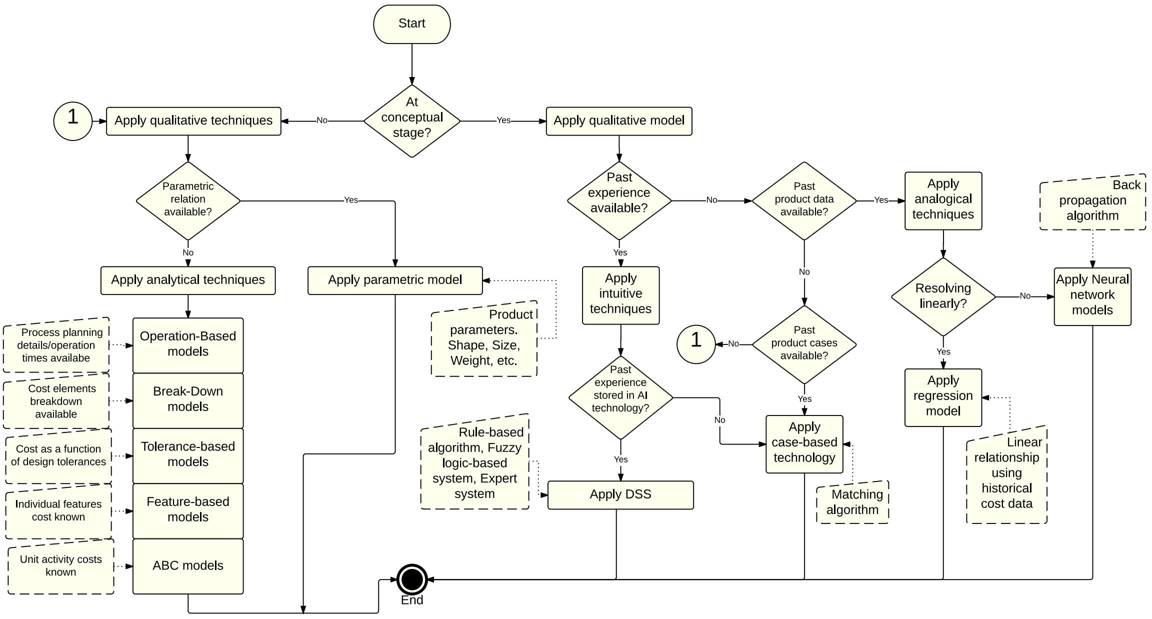


Figure 2-4: Decision model for selection of cost estimation method according to Niazi[37]

Concerning aircraft manufacturers

According to Curran et al.[44], cost associated to the complex task of designing and producing aircraft can be broken down in the following six categories:

Material costs It includes raw and finished material costs.

Fabrication costs This important part includes cost drivers such as technical specifications, manufacturing philosophies and labor rates.

Assembly costs They use the same cost drivers as the fabrication costs. Together with the two first costs, they form the manufacturing costs.

Support costs It includes the quality inspection, redesign and rework after the production. These costs are relatively small and usually around 5% of the manufacturing costs.

Amortization costs This includes non-recurring costs of tooling, methods and design.

Miscellaneous costs These are usually small at around 5% of the total costs.

Concerning aircraft operators

Traditionally, the first dichotomy operated by airlines concerning their accounts is in operating and non-operating. On one hand, non-operating costs are not related to the airline performance since they are not part of the airline's core business. On the other hand, operating costs and revenues are good performance indicators.

The operating costs are classified in two main categories: the Direct Operating Costs (DOC) (defined as all the costs required to keep the aircraft flying) and the Indirect Operating Costs (IOC) (related to the passengers). According to Doganis[45], the cost-break-down of aircraft operator is as follows:

1. **Direct Operating Cost**
    (a) Flight operations
        i. Flight crew salaries and expenses.
        ii. Fuel and oil.
        iii. Airport and en-route charges (landing fees depending on Maximum Take-Off Mass [kg] (MTOM), passenger charge based on departing passengers and navigation services and other aids).
        iv. Aircraft insurance (usually around 1.5-3% of the aircraft purchase price).
        v. Rental/lease of flight equipment/crews (could be considered depreciation instead).
    (b) Maintenance and overhaul
        i. Engineering staff costs.
        ii. Spare parts consumed, workshops, maintenance hangars, offices.
        iii. Maintenance administration (could be IOC)
    (c) Depreciation and amortization
        i. Flight equipment
        ii. Ground equipment and property (could be IOC)
        iii. Extra depreciation (in excess of historic cost depreciation)
        iv. Amortization of development costs and crew training.
2. **Indirect Operating Cost**
    (a) Station and ground expenses
        i. Ground staff.
        ii. Buildings, equipment, transport.
        iii. Handling fees paid to others.

   (b) Passenger services
      i. Cabin crew salaries and expenses (could be DOC).
      ii. Other passenger service costs (like catering, delays in flights,. . .).
      iii. Passenger insurance.
   (c) Ticketing, sales, and promotion (general and administration).
   (d) Other operating costs

Finally, some key performance indicators of financial health of aircraft operators are:

The profit margin:

$$PM = \frac{Profits}{Revenues} = \frac{Revenues - Costs}{Revenues} = 1 - \frac{Costs}{Revenues} \tag{2-1}$$

The revenues:

$$R = Yield * Pax * Dist * NbrFlights \tag{2-2}$$

Where,

R = Revenues
$Yield$ = Revenue / passenger / nm
Pax = Number of passengers transported per flight (on average)
$Dist$ = Flown distance in nm
$NbrFlights$ = Number of flights done

2-3 Methodology and limitations

This research is divided in four steps as displayed in figure 2-5.
The first step is programming a module to design a family of aircraft. It serves as basis for comparison for the, yet to be investigated, modular aircraft. An overview of the activities is given in figure 2-6 where the main activity is the "Fleet assignment" part. In the case of a network made out of 10 destinations, every destination has one ideal aircraft that can be designed for that particular route and demand. The principal limitation is that the family is going to be composed out of those 10 ideal aircraft.

The second step is performing a structural analysis in order to estimate the mass penalty of a connection mechanism of the fuselage. This is done in two phases: first defining the loads acting on the fuselage in different load cases; then sizing the connection mechanism by idealizing it as bolt connection. An important limitation is that the fuselage is modelized as a one-dimensional beam where the weight of the aircraft is a constant distributed load and the lift is a constant distributed load in the middle of the fuselage.

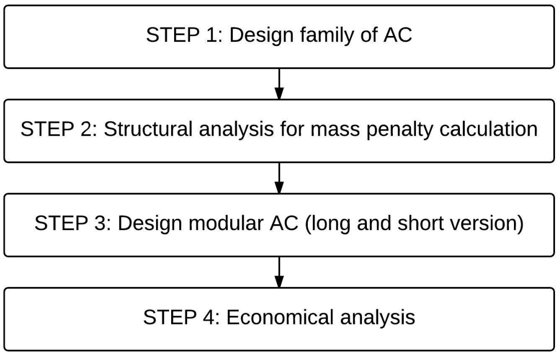


Figure 2-5: General methodology

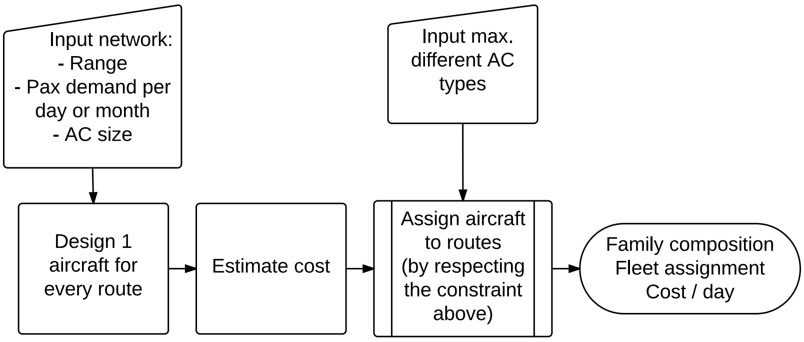


Figure 2-6: Step 1: Design aircraft family

The third step is to investigate the modularity of aircraft. The goal is to obtain a geometry, mass and performance estimation of the modular aircraft in both its short and long versions. The fuselage length is changed to accommodate the change in passenger capacity. But so is the configuration of the aircraft which is: the tail (vertical and horizontal), the landing gear and the engines). The overview of the methodology is shown in figure 2-7. For a detailed flowchart adapted from Lewis[46], see appendix B.

Next the performance (fuel consumption) of the modular aircraft is compared to a regular aircraft on one specific route with varying passenger demand of 35% between high and low season. This value of 35% is chosen based on the computation in section 1-2 (page 1) and interviews conducted with airlines. An overview is given in figure 2-8 on page 18. The principal limitation is the assumed passenger demand.

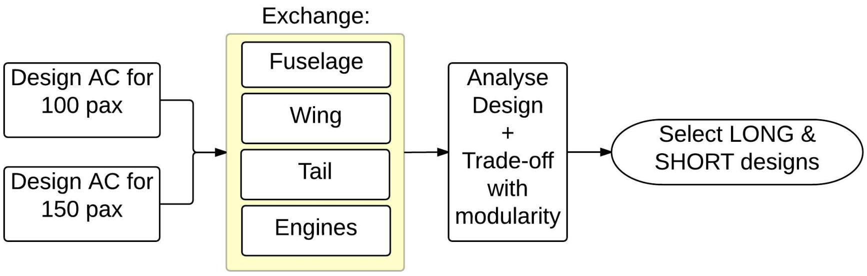


Figure 2-7: Step 3: design modular aircraft

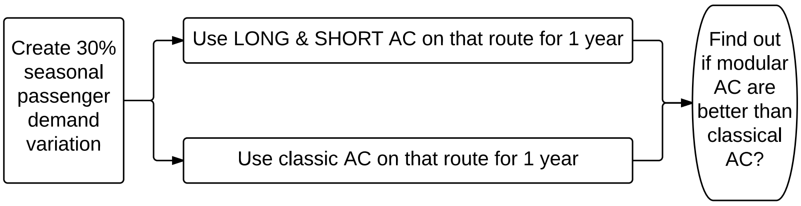


Figure 2-8: Step 4: Economical analysis

Chapter 3

Modular aircraft concept definition

This chapter is divided in two parts. Section 3-1 presents the aircraft concept and section 3-2 presents the fuselage design requirements.

3-1 Concept definition

The concept is best summarized in figure 3-1. The goal is to change the capacity of the aircraft twice a year to accommodate the increase in passenger demand during high-season. For this concept, the wing stays the same for both the long and short version, otherwise the change in configuration would be much to complicated to perform in a short amount of time during the operational life of the aircraft. Concerning the landing gear, tail and engines, they can be changed if necessary. Another situation might be interesting: changing the length of the fuselage a few times over the lifetime of the aircraft to adapt its capacity to the market demand.

There are many variables with respect to the fuselage:

Fuselage length: obviously, in order to carry a different number of passengers, the length of the fuselage changes and the diameter stays constant.

Number of plugs: one would be ideal to facilitate the modification between the long and short version of the aircraft. But to satisfy weight distribution and handling qualities, two plugs might be required.

Position of the plugs: either close to the wingbox, where the fuselage needs to be the strongest or at the end, where the structure is the simplest.

Concerning the engine, tail and landing gear, they might have to be changed according to the configuration of the aircraft.

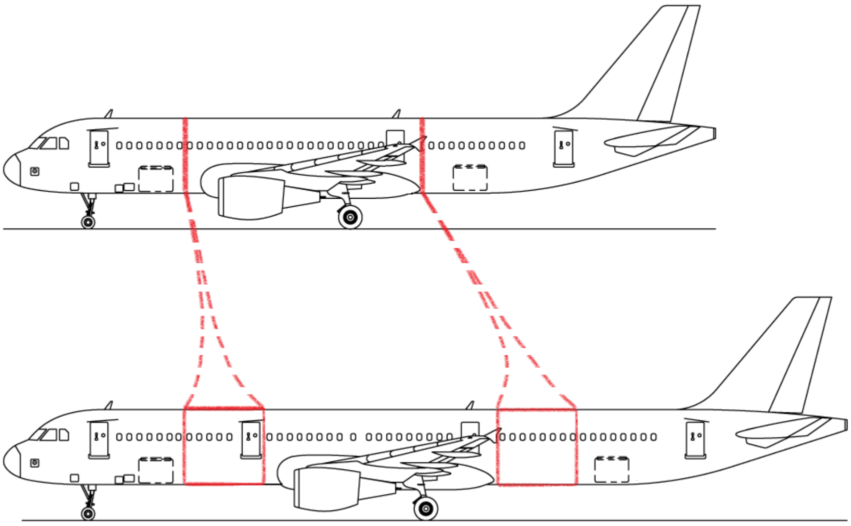


Figure 3-1: The modular fuselage concept

3-2 Fuselage design requirements

This section considers the airworthiness regulations requirements applicable for the fuselage design, focusing on three points: safety, passenger well-being and airline requirements.

3-2-1 Safety

A very important safety aspect is the type and number of emergency exit doors on the airplane. According to CS-25.803(c)[47], all aircraft having a seating capacity of more than 44 passengers should be possible to be evacuated in less than 90 seconds.

Since Amendment 12 of CS-25 in July 2012, the regulation concerning the number of emergency exits required has changed. The maximum number of passengers seats permitted depends on the number and type of emergency exits installed on each side of the fuselage as displayed in table 3-1. The classic configuration for 100 passenger is two Type I exits at the front and back plus 1 Type III over-wing exit. The 150 passenger version has one extra Type III over-wing exit.

All exits types require 1 attendant to operate in case of emergency, except Type A and B that need two. As a result, the long version requires one flight attendant more than the short version.

Figure 3-2 displays the type and layout of the emergency exits for the 100 passengers version.

Exit type	Passenger seats permitted
Type A	110
Type B	75
Type C	55
Type I	45
Type II	40
Type III	35
Type IV	9

Table 3-1: Passenger seats allowed per pair of emergency exit

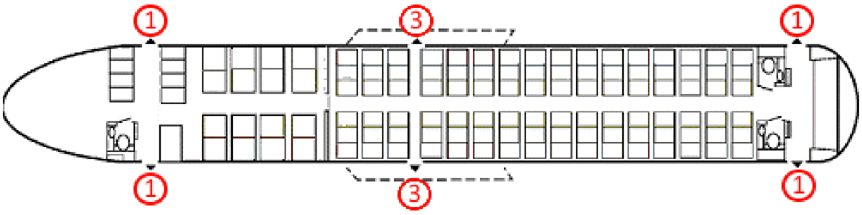


Figure 3-2: Emergency exits type and layout for a classic 100 passenger aircraft

3-2-2 Passenger well-being

Passenger demand for the comfort and service level depend on their cultural background, wealth, time and type of airline [48]. As a result, the cabin requirements concerning the class ratios, seat pitch and dimensions, toilets, galleys and crew members per passenger and cargo compartment vary widely. Airbus advises a maximum of 50 passengers per flight attendant in a single class, high-density configuration. But this requirement is less constraining than the required number of attendants per exit.

3-2-3 Airline requirements

The airlines that have to buy and operate the modular aircraft have their own requirements as well. As all businesses, they strive to maximize their shareholder's return. This directly imply low operating costs and a fuel efficient aircraft. Those two points are the weak aspects of the modular design. However another key aspect for airlines where the modular aircraft concept is ideal for is: flexibility. Indeed, the trend in the airline industry is to increase as much as possible the load factor of the aircraft and use the correct size for the routes as can be seen in figure 3-3.

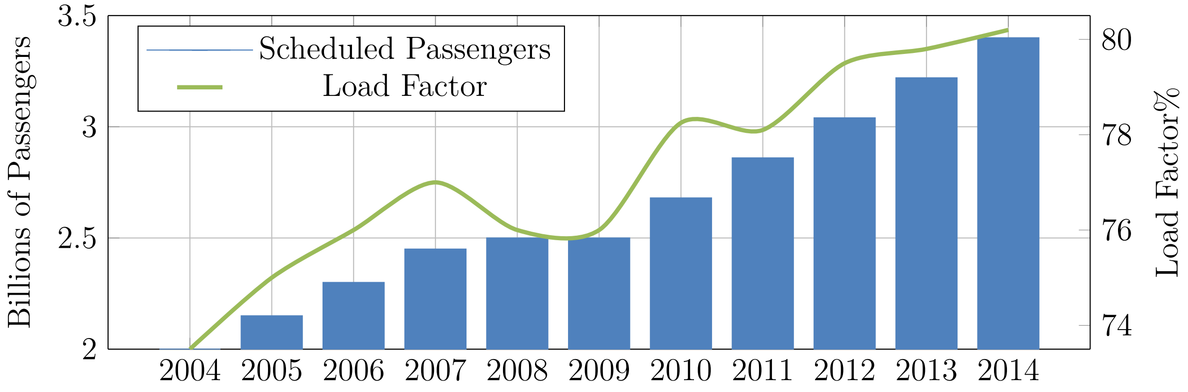


Figure 3-3: 2004-2014 Global Airline Scheduled Passengers

Chapter 4

Family aircraft design

This chapter is divided in three parts. Section 4-1 describes the tool. Section 4-2 validates the tool with many different test cases. Finally, a conclusion is drawn in section 4-3.

4-1 Tool description

The goal of this tool is to design a family of aircraft based on a fixed network and seasonal demand. The desired limit of different aircraft in the family is decided by the user. Then the tool designs, selects and assigns the best aircraft according to the cost of flying and ownership of the fleet.

Linear programming is chosen as optimization technique because it handles integer problems very well. There are limitations to it. Firstly, the underlying assumption is that modeling the cost of aircraft using a linear model is suitable. This is of course not necessarily the case. Indeed, the two linear properties: *additivity* & *proportionality* preclude interaction between variables. For instance, depending on the number of similar aircraft types in a fleet, economies of scale can be made which is not reflected in a linear model. Nevertheless, for a conceptual approach, not many details allowing for a better cost estimate are available. Secondly, the *proportionality* property (for instance, for the objective function, the cost is directly proportional to the level of use of a variable) forbids efficiency improvements or other non-proportional behaviors but this is not an issue here. Thirdly, a weakness common to all modeling techniques is assuming that the input data is perfectly accurate. This is why *sensitivity analysis* is applied: to know how useful the answer is if the input data is of poor quality. As a result, a linear approximation can be used.

The equations, constraints and variables required to define this linear programming tool are given on the following page.

Objective function:

$$\sum_r \sum_k y_{r,k} \cdot CASK_k \cdot dist_r \cdot seats_k + \sum_k N_k \cdot OwC_k \tag{4-1}$$

Where:

$y_{r,k}$ = frequency of flying route r with aircraft type k (Decision variable)
$CASK_k$ = Cost per Available Seat Kilometer for aircraft type k. It is the total operating costs divided by the ASK, where ASK is the number of seats available times the km those seats are flown (in €, Parameter)
$dist_r$ = length of route r (in km, Parameter)
$seats_k$ = number of seats in aircraft type k (Parameter)
N_k = number of aircraft of type k in fleet (Decision variable)
OwC_k = cost of ownership[1] of aircraft type k (in €, Parameter)

Subject to the following constraints:
Demand verification:

$$x_r = dem_r \quad , \quad \forall r \in \mathfrak{Re} \tag{4-2}$$

Capacity verification:

$$x_r \leq \sum_k y_{r,k} \cdot cap_k \quad , \quad \forall k \in \aleph, \quad \forall r \in \mathfrak{Re} \tag{4-3}$$

Aircraft availability:

$$\sum_r FT_r \cdot y_{r,k} \leq BT_k \cdot N_k \quad , \quad \forall k \in \aleph, \quad \forall r \in \mathfrak{Re} \tag{4-4}$$

Maximum number of aircraft types requires the following two constraints:

$$N_k \leq \overline{M} \cdot \delta_k \quad , \quad \forall k \in \aleph \tag{4-5}$$

$$\sum_k \delta_k \leq MNT \quad , \quad \forall k \in \aleph \tag{4-6}$$

Where:

x_r = number of passengers transported on route r (Decision variable)
dem_k = demand of passenger on route r (Parameter)
cap_k = capacity of aircraft type k = $seats_k \cdot$Loading Factor (Parameter)
FT_r = time to fly route r (Parameter)
BT_k = number of hours an aircraft can fly (Parameter)
$\overline{M}$ = large number (Parameter)
δ_k = binary, tells if aircraft k is present in fleet (Decision variable)
MNT = max number of different aircraft types (Parameter)

The parameters are defined by the user and the decision variables are computed by the tool using operations research theory for Mixed Integer Programming (MIP) since all variables are integers and there is one binary variable: δ_k.

---

[1] Defined as lease cost plus depreciation[45]

4-2 Verification test cases

Several test cases have been devised to test all the parameters of the tool. The parameters have been defined in equations 4-1 to 4-6.

4-2-1 Case 1: basic test of simple network with 4 routes

Presentation

Table 4-1 displays the test case where the network has only 4 routes. The first two ones are very similar and the two last ones are also very alike. In this case the user asks for two aircraft types in the fleet. So the obvious solution is to select the aircraft designed for routes 1 and 3, have two of each to serve the 4 flights.

Route	**Distance (km)**	**AC capacity**	**Demand**
1	9000	296	296
2	8100	290	290
3	3400	150	150
4	3000	144	144

Table 4-1: Simple test case for the family design tool

Aircraft types performances and costs

For those 4 routes, 4 ideal aircraft exist. The principal aircraft characteristics are displayed in table 4-2. See appendix C for the complete list of characteristics.

Parameter	**AC1**	**AC2**	**AC3**	**AC4**
Seats	296	290	150	144
Range (km)	9000	8100	3400	3000
Payload Mass (kg)	34500	31050	20400	18360
d_{T-O} (m)	3000	3000	1960	1960
d_{land} (m)	1964	1964	1509	1509
M_{cruise}	0.78			
Alt_{cruise} (m)	11278			

Table 4-2: Main input parameters for the 4 aircraft.

Parameter	**AC1**	**AC2**	**AC3**	**AC4**
Cost per Available Seat Kilometer (CASK) (€)	0.052	0.051	0.032	0.031
Cost of ownership (€/day)	31250	31249.7	8750	8733.3

Table 4-3: Cost for the 4 aircraft.

The cost characteristics of those 4 resulting aircraft are displayed in table 4-3. Finally, the user can chose to display for instance the cheapest solutions within 3% of the optimal one. All these parameters are entered in the tool which then provides the optimal solutions in the following form:

- Specifies if the solution is unique or not. If not, all solutions with same costs are displayed.
- Optimality rank of the solution: the optimal solution is number 1; then increase as they because less optimal.
- Number of different aircraft types required.
- Cost (in million €per day).
- Fleet composition.
- Routes assignment.

Results

The solution is:

```
All RELEVANT solutions are unique.
===>Solution number 1<===
Solution number 1 requires 2 different AC types and costs 0.32408 mEuro/day.
The fleet is composed of:
2 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

Analysis

As expected, it turns out that the cheapest alternative is to have two aircraft of type 1 and two aircraft of type 3 and have them fly routes 1 plus 2 and 3 plus 4 respectively.

4-2-2 Case 2: maximum number of different aircraft types in fleet

The goals of this test is to limit the number of aircraft to 1, not 2 since it was already tested in Case 1, 3 and 4 (which is essentially turning off the purpose of the tool).

All inputs are the same as in case 1, except the Maximum Number of different aircraft Types (MNT) which is tested for three values (1, 3, 4)

The tool limits the number of aircraft types to 1, 3 and 4. Moreover, in the last case, every aircraft designed for one particular route is assigned to the correct route.

4-2-3 Case 3: increasing the passenger demand

This test is done for all 4 routes: adding one passenger at the time on the route to add one aircraft.

This time, the *Demand* column of table 4-1 is changed to 297 for the first test, 291 for the second test, 151 for the third test and 145 for the fourth test. Also, the MNT is again 2.

Adding one passenger has the expected effect: when it is on the larger route (serviced by aircraft 1 or 3) it forces an extra aircraft to be used. But when the demand is increased is on the shorter routes (routes 2 or 4) this is not the case: since those routes are catered by aircraft 1 and 3 which have a higher capacity, they can easily carry the extra passenger.

4-2-4 Case 4: decreasing the passenger capacity

This test is done for all 4 routes: decreasing the seating capacity by 1, one aircraft at the time.

This time, the *AC capacity* column of table 4-1 is changed to 295 for the first test, 289 for the second test, 149 for the third test and 143 for the fourth test.

As in case 3, it only has an impact for aircraft 1 and 3. So it is coherent with the expectations.

4-2-5 Case 5:increasing the distance

The goal is to increase the route length beyond the range in the available block time. This should trigger an alert. When changing the distance from 7000 to 9000km for the first route and aircraft, the following alert is given:

```
WARNING: AC type 1 has insufficient block time to complete the fligth.
```

This is an important check to verify that the bloc time and flight time are taken care of properly.

4-2-6 Case 6: decreasing the Cost per Available Seat Miles

The CASK of every aircraft is changed to 0, one at the time. They are all as expected: favoring the aircraft with 0 CASK, except when that aircraft has insufficient range to reach a particular destination: then it is the optimal aircraft that is assigned to that route. When the fourth aircraft has 0 CASK, it is not selected to fly a destination because the limit to two types of aircraft is stronger and as a result, the original solution (aircraft 1 and 3 respectively flying on routes 1-2 and 3-4) is selected. This is also a very interesting case that works correctly.

4-2-7 Case 7 : decreasing the Cost of Ownership

It is interesting to note that is has no impact on the assignment aircraft-route because the CASK is more important. This is verified when changing the Cost of Ownership (OwC) of aircraft 2 to 0 and changing its CASK to the same as the cheapest aircraft (4). In that case, only aircraft 1 and 2 are chosen. This demonstrates that the OwC is correctly taken into account.

4-2-8 Case 8: increasing the number of aircraft and destinations

Up to now, there were only 4 routes with their 4 optimal aircraft and limited to two aircraft type in the family. To check if the tool works for larger networks, it is tested for 4 to 8 routes. It still performed well except for one minor issue: speed. Indeed, the calculation time is affected by network size as can be seen in table 4-4. Also, the more different aircraft types are allowed in the family, the longer the computation time.

4-3 Conclusion

To conclude, the family design tool works well and can handle the different limit cases. The only weakness is its computation speed. It can be improved by using the multi-core processing options of Matlab. But the performances are still quite slow for larger networks. All the detailed solutions of the cases presented can be found in appendix F.

Network size	Computation time
4	1 (sec)
5	4 (sec)
6	10 (sec)
7	11 (min)
8	20 (min)

Table 4-4: Computation performance as a function of the network size to obtain a family of two aircraft on an i7 processor.

Chapter 5

Conceptual aircraft design

This chapter is divided in five sections. Firstly, a tool selection is done in section 5-1. Secondly, typical results of the selected tool are displayed in section 5-2. Thirdly, section 5-3 gives the different modifications that have been required to design a modular aircraft with the selected tool. Next, section 5-4 verifies in three ways that the tool works properly. Finally, section 5-5 gives the user manual of this tool.

5-1 Tool selection

Why is an aircraft conceptual design tool required? The goal of the research is to investigate a new aircraft concept to find out if it is better than current solutions. In order to evaluate the new concept's performances, it should be compared to a reference. The conceptual design tool is required to establish that reference and then compare the new concept to it.

There are many different tools available. Hereunder is a list with their principal characteristic highlighted:

DEE Preliminary aircraft design tool using multi-fidelity and KBE analysis tools developed at the TU Delft [49].

CAESIOM Freeware preliminary aircraft design tool using multi-fidelity developed by CFS Engineering [50].

VAMPzero Open source conceptual design tool using handbook methods [51].

Prado Preliminary design and optimization tool using physics based aerodynamics and in-house Finite Elements (FE) for structure analysis. Developed by the TU Braunschweig [52].

Piano Preliminary aircraft design tool using semi-empirical methods for aerodynamics and structures analysis developed by the company Lissys [53].

Flops Preliminary design tool using analytical analysis for flight performance in a gradient based Multi-disciplinary Design Optimization (MDO) tool but no geometry module. Written by Arnie McCullers at the NASA [54].

Pacelab APD Preliminary design using Raymer/Toorenbeek handbook methods [55].

PreSTO Preliminary sizing excel sheet using semi-empirical (handbook methods) developed by the Hamburg University[56]

ACSYNT Preliminary design tool using semi-empirical methods [57].

RDS Preliminary aircraft design software by Daniel Raymayer based on semi-empirical methods [58].

AAA Preliminary aircraft design tool based on the method outlined in Airplane Design I-VIII by Roskam [59].

ADS Conceptual design tool using semi-empirical methods (Roskam)[60].

Airplane PDQ Interactive airplane modeler for conceptual design [61].

RAGE Software for parametric aircraft modeling and exporting but it is not a design tool [62].

openVSP same as RAGE [63].

openCDT Open source conceptual aircraft design tool and framework with little available information [64].

PADLab Preliminary aircraft design tool tailored towards the cabin design. Developed by the TU Berlin [65].

J2 Builder Geometry modeler for the J2 universal framework but it is not a design tool [66].

pyACDT Object-oriented design framework for conceptual design using multi-level fidelity analysis methods [67].

The selected tool is the Design and Engineering Engine solution (DEE), and more precisely, the Initiator which is the conceptual aircraft design part of the DEE. Within the faculty of Aerospace Engineering a computer aided design framework called the DEE has been developed. It consists of a collection of multidisciplinary design and analysis tools, aimed at automating the non-creative and repetitive design activities[68]. One of the modules of that framework is The Initiator software. It is a collection of sizing tools able to provide an optimized geometry and performance evaluation of aircraft based on a set of top level requirements. Its main advantages compared to the other softwares are: Class II.V weight estimation, which combines analytical analysis and empirical data for the wing and fuselage structure; also, it is readily available.

The high-level design process of the Initiator is represented in figure 5-1. The process starts with a definition of the top level requirements and the input of the database for a set of performance parameters (it is an initial guess of the drag polar, specific fuel consumption and $C_{L_{max}}$). First a Class I weight estimation is done. Then the wing loading and thrust-to-weight ratio is determined in the design space constrained by performance and regulatory requirements. After, a Class II weight estimation [69] is performed to improve the weight and center-of-gravity estimations. The class II weight estimation serves as input for the aerodynamic analysis which uses a vortex-lattice method. Because it is an inviscid analysis method, the profile drag is calculated separately in the parasite drag estimation module using Torenbeek's[70] empirical method. Then those results are used in the Class II.V weight estimation. After every design loop, the weight calculated by the Class II.V routine is compared with the previous iteration of Class II.V. If the MTOM deviation is larger than 1%, the weight and performance data are sent back to the Class I module and the loops starts over. Else, when the weight has converged, the range is tested. If the range

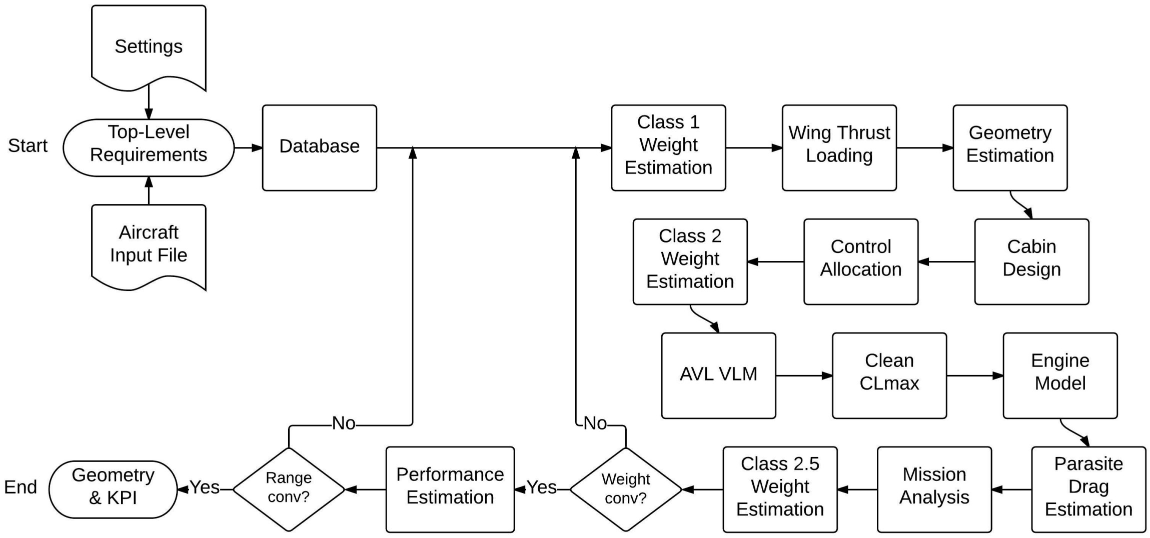


Figure 5-1: Overview of the current activities of the Initiator design tool

deviation is larger than 1%, the whole weight convergence loop is repeated.

5-2 Typical results of the Initiator

The complete inputs required to obtain an optimized aircraft from the design tool are listed in appendix C. Once the optimization has converged, a report is created with the following data. See appendix D for the figures.

Aircraft geometry Figure D-1 represents the geometry of the optimized aircraft. All the dimensions are presented in tables and the fuel tank layout is displayed in a figure as well (not shown).

Operational performance Three diagrams are computed and displayed. First the loading diagram (T/W-W/S) is displayed together with the optimal design point. For an example, see figure 5-3 (page 39). Secondly, the payload-range diagram and the flight envelope are calculated as can be seen in figure D-2.

Weight estimation The principal masses such as MTOM, Zero Fuel Mass [kg] (ZFM) are given as well as the mass of every component (Engine, Furnishing, Fuselage, Main Gear,. . .). The center of gravity locations for the MTOM, ZFM and Operating Empty Mass [kg] (OEM) are computed and the loading diagram is computed as well (see figure D-3).

Aerodynamics Different aerodynamic properties at cruise are computed as well as the drag polar and aerodynamic efficiency of the aircraft as can be seen in figure D-4.

A complete analysis of the output of the tool has shown that it works well in this article [71].

5-3 Modifications required for modular aircraft design

Since the tool is not originally designed to analyze non-optimum aircraft, some modifications are necessary. The elements of the aircraft that need to be defined are: fuselage, wing, tail and engines. The fuselage can already be taken care of in the actual state of the Initiator but the three others need modifications.

5-3-1 Modifications required for the engine

The engine is the simples of the 3 parts (engine, wing, tail) that require a modification on the Initiator. The reason is because it is sized at the very beginning of the optimization process. The first of the 2 modification occurs in the Class I weight estimation. Since the MTOM and OEM are known precisely enough for the Class I weight estimation, they can be input here already. Secondly, those masses are used to compute the loading diagram (example in figure D-1). Originally, this diagram serves to find the design point. But since the desired thrust is already known, it does not need to be computed anymore. Subsequently, the engine is sized only according to the thrust. So the rest (positioning, sizing, weight,. . .) is taken care of.

5-3-2 Modifications required for the wing

The wing is completely defined with only 3 parameters. Two for the geometry: the span and the root chord are enough since the taper ratio and aspect ratio are fixed. The mass of the wing is the last parameter. It appears in the Class II, Class II.V and EMWET weight estimations where the software also requires modifications. Because of all the interactions, a few more parameters have to be taken into account as displayed in appendix E, table E-2, column *wing*.

5-3-3 Modifications required for the tail

The tail is composed of the vertical and horizontal tail. They are both treated as wings so they both have similar parameters to the wing.

5-3-4 Implementation in the code

To allow for the modularity analysis of the wing, tail and engine, 9 files need to be modified as described in appendix E, table E-1.

5-4 Verification test cases

5-4-1 Methodology

To verify that this method works as expected, all 4 aircraft parts (fuselage length, wing, tail and engine) are being changed one at the time as well as together to cover all possible combinations. The verification procedure is based on 2 aircraft: a small one of 100 passengers and a larger one of 150 passengers. Both are optimized with the initiator, then parts are exchanged. For example, the engine of the larger plane is fitted on the smaller plane, then the result is analyzed according to the following 3 characteristics: weight and dimensions, geometry and the design points.

The input for the Initiator of the small and large versions are given in table appendix C.

The 4 parts (fuselage length, wing, tail and engine) all have 2 possibilities (small or large version) which mean there are 16 combinations as shown in table 5-1.

Characteristics				**Configuration**	
Fuselage Length and main basis	**Wing**	**Tail**	**Engine**	**Name**	**Number**
100pax	small	small	small	100WsTsEs	1
			large	100WsTsEl	2
		large	small	100WsTlEs	3
			large	100WsTlEl	4
	large	small	small	100WlTsEs	5
			large	100WlTsEl	6
		large	small	100WlTlEs	7
			large	100WlTlEl	8
150pax	small	small	small	150WsTsEs	9
			large	150WsTsEl	10
		large	small	150WsTlEs	11
			large	150WsTlEl	12
	large	small	small	150WlTsEs	13
			large	150WlTsEl	14
		large	small	150WlTlEs	15
			large	150WlTlEl	16

Table 5-1: The 16 configurations. Configuration 1 and 16 are optimal for the 100 pax and 150 pax versions respectively.

5-4-2 Weight and dimensions

The two optimal aircraft are:

- for 100 passengers: Configuration 1
- for 150 passengers: Configuration 16

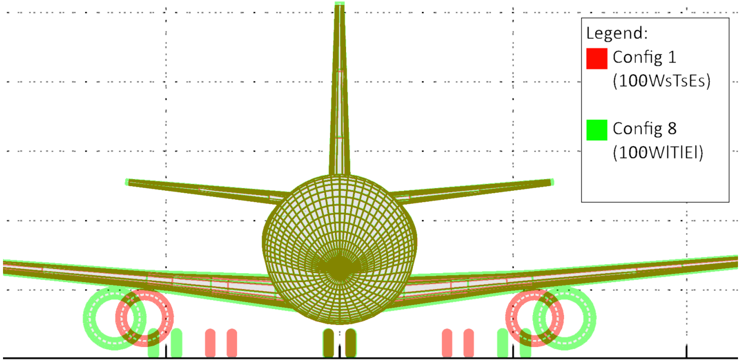
Their specifications are displayed in table 5-2. Obviously, the wing and engines of the large 150 pax aircraft are larger than that of the small 100 pax aircraft since the payload increases by 50% from the small to the large aircraft. However, it is interesting to note that the tail have very similar span and root chords as can be seen in table 5-2. It could be expected that the tail of the large aircraft would be much larger. But since the distance between the center of gravity and the tail is larger as well, there is hardly any difference.

	Variable	**Config 1** **100WsTsEs**	**Config 16** **150WlTlEl**
Fuselage	Length (m)	27.67	41.51
	Diameter (m)	4.3	
	Pax. capacity	100	150
Main wing	Mass (kg)	5137	7919
	Span (m)	32.1	37.04
	Wing pos. from nose (m)	9.10	14.77
	Root chord (m)	6.68	8.08
Tail	HTail mass (kg)	642	747.26
	HTail span (m)	12.12	12.31
	HTail root chord (m)	3.59	3.65
	VTail mass (kg)	400	605.19
	VTail span (m)	5.36	5.84
	VTail root chord (m)	5.32	5.4
Engine	Mass (kg)	2190	2793
	Diameter (m)	1.63	2.01
	Length (m)	3.16	3.61
	Thrust (N)	75864	112975
AC	Ref Area (m^2)	108.47	144.4
	Ref Chord (m)	4.11	4.74
	MTOM (kg)	52672	78291
	OEM (kg)	30359	40140
	Fuel Mass (kg)	10232	14677
Perf	Consumption (l/pax/km)	2.1317	2.0384
	T/W	0.2936	0.2942
	W/S	4764	5319
	Range (km)	4800	

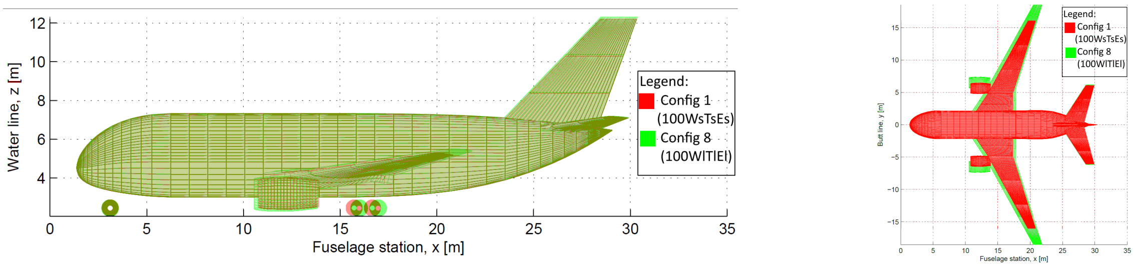
Table 5-2: Mass and dimensions of the 2 optimal aircraft

5-4-3 Geometry

The first step to check if the exchange of wing, tail and engines work properly is to perform a geometrical analysis. The test case presented here is checks if it is possible to start with the optimal small aircraft and exchange its wing, tail and engines with those of the large aircraft. So the aircraft still carries 100 passengers but is not optimal anymore because its wing, tail en engine are over-sized. This gives configuration 8.
Checking the 3 views allows to compare the geometry to see if the change has occurred as expected. Figure 5-2 (a) clearly displays the difference in engine and tail size between the optimal aircraft carrying 100 passenger and its version with the large wing, tail and engines. Figure 5-2 (b)& (c) shows the difference in engine size and vertical tail size as well as the difference in wing and engine size and horizontal tail span.



(a) Front View



(b) Side View

(c) Top View

Figure 5-2: Front view, side view & top view of the optimal aircraft for 100 passengers (Config 1) and Config 8 (also 100 passenger but with large wing, tail and engines)

5-4-4 Design point comparison

As identified in the previous sections there are 2 optimal aircraft: cases 1 and 16 for the 100 passenger and 150 passenger aircraft respectively. The 14 other cases are modifications based on these two. To verify that the modular tool works correctly, the design point of the 14 non optimal configurations are checked against the optimal configuration carrying the same number of passengers. So configurations 1 to 8 are plotted in figure 5-3 (since they all have a capacity of 100 passengers) and configuration 9 to 16 are plotted in figure 5-4 (since they all have a capacity of 150 passengers) .

Configurations 1-8, based on the small aircraft

The optimal design point (configuration 1) is identified by a red dot in figure 5-3. The 7 other configurations are also plotted on it. This allows for a quick verification that the different configurations move in the correct directions in the graph. Configuration 2 is simply the optimal small aircraft with large engines. A larger engine means more thrust and more weight. The aircraft should move up and to the right on the graph, which it does.

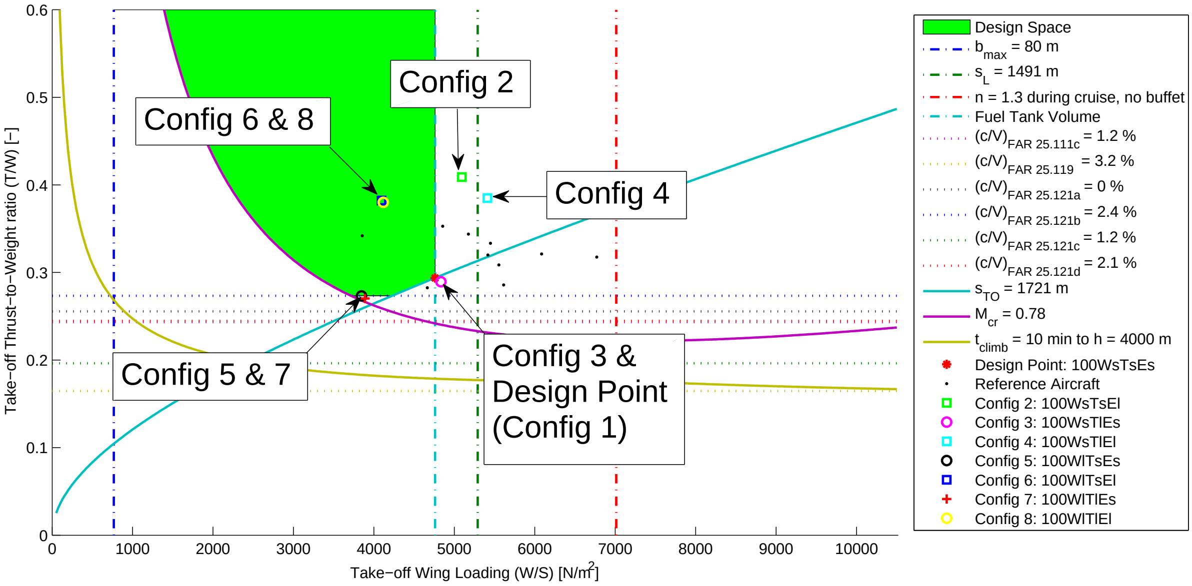


Figure 5-3: Optimal design point of the small aircraft with the 7 configurations variants

Configuration 3 is simply the optimal small aircraft with large tail. A larger tail changes only the weight. The aircraft should move down and to the right on the graph, which it does.

Configuration 4 has a larger tail and engines. This means an increase in weight and thrust. The aircraft should move up and to the right on the graph, which it does.

Configuration 5 has only a large wing. This increases the weight a little bit and surface largely. The aircraft should move down and to the left, which it does.

Configuration 6 is the same as 5 but with a large engine. A larger engine means more thrust and more weight. So with respect to configuration 5, the aircraft should move down and to the right on the graph; in the same fashion as configuration 2 moves with respect to the optimal design point. This is exactly what occurs.

Configuration 7 is the same as 5 but with a large tail. A larger tail changes only the weight. The aircraft should move down and to the right on the graph; similar to point 3 moving with respect to the optimal design point. This is exactly what occurs.

Configuration 8 has all the characteristics of the large aircraft with the short fuselage. So compared to the optimal small aircraft, it has a large wing and engines. So the aircraft should move up and to the left which it does.

As it can be seen, there are may configurations out of the green zone (the design space) in figure 5-3. It means that those configurations violate the constraints and cannot be selected as viable design points. However, it is good that the tool can plot them on the diagram. It means that the design tool works as expected.

Configurations 9-16, based on the large aircraft

The optimal design point is identified by a red dot in figure 5-4. The 7 other configurations are also plotted on it. This allows for a quick verification that the different configurations move in the correct directions. Configuration 9 is the small aircraft's wing, tail and engine with the long fuselage. Because of the large increase in weight due to the fuselage, both the T/W and W/S experience large changes: the T/W decreases and the W/S increases.

Configuration 11 is similar to 9 but with the large tail. This increases the weight. The aircraft should move down and to the right on the graph, which it does. The change is very small compared to the change between configuration 1 and 3 in figure 5-3, this is because the MTOM of the aircraft carrying 150 passenger (figure 5-4) is much larger.

Configuration 12 has simply the small wing. This decreases the weight and drastically diminishes the surface. The aircraft should move to the right and up compared to the optimal design point, which it does.

Configuration 10 has small wings and tail. So it moves up and to the right with comparison to the optimal design point. Then compared to configuration 12, it has the small tail. Thus the weight of configuration 10 is slightly smaller than that of configuration 12. As a result, configuration 10 should be slightly higher and to the left compared to configuration 12, which is the case.

Configuration 13 has a small tail and engines compared to the optimal design point. It

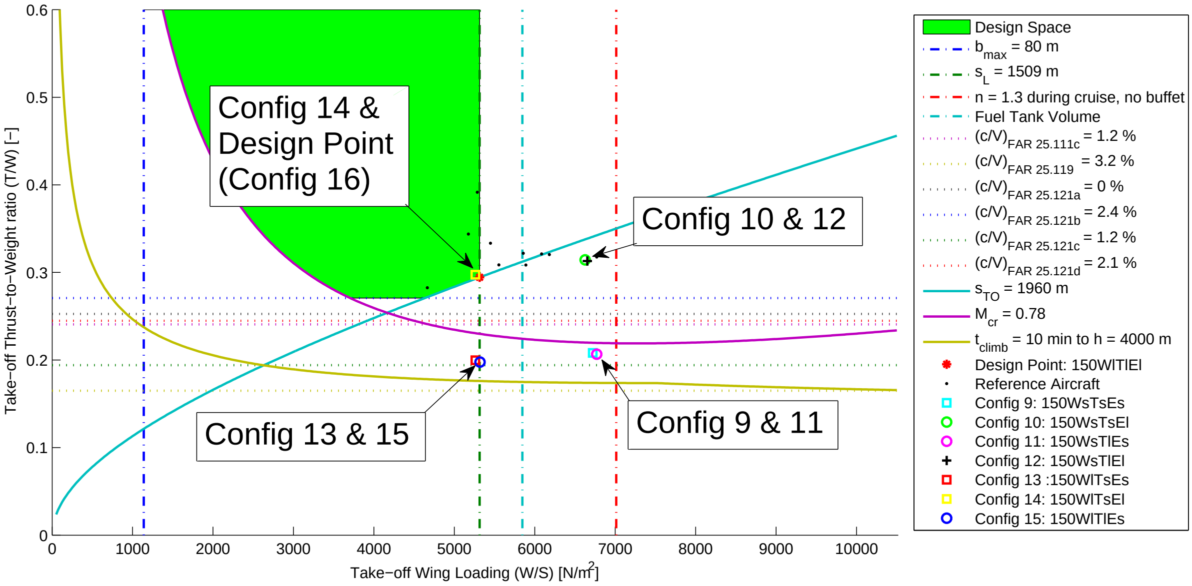


Figure 5-4: Optimal design point of the large aircraft with the 7 configurations variants

means that the weight is lower. The aircraft should move down by a large distance and to the left slightly, which it does.

Configuration 15 is similar to 13, but with a large tail. It increases the weight compared to configuration 13. The aircraft should move down and to the right on the graph compared to aircraft 13, which it does.

Finally, configuration 14 is similar to the optimal configuration (16) but with a smaller tail. Tis results in a lighter weight. So the aircraft should move up and to the left, which it does.

To conclude, it can be seen that the following 3 characteristics: weight and dimensions, the geometry and design point all confirm that the modular design tool works properly.

5-5 User Manual

The procedure to use those new functionalities allowing to install a particular wing or tail or engine on an aircraft is described in this section. The functionality used is InputModule. To define one element, multiple inputs are required. The table summarizing which input is required for which desired part of the aircraft is given in appendix E, table E-2.

An example of the ModuleInput functionality being used to define an aircraft in the modified Initiator is given in appendix E. This should be copied in the .xml file of the aircraft.

To summarize:

1. Install this version of the initiator.
2. In the .xml file of the aircraft that is going to be analyzed, add the ModuleInput as given in appendix E (modified according to the needs).
3. Run the Initiator tool in Matlab.

Chapter 6

Structural analysis of the Modular Fuselage concept

The method for estimating the weight of the connection mechanism is based on the structural analysis of bolt connections. This chapter is divided in four sections. The section 6-1 estimates the loads acting on the fuselage. Section 6-2 uses those loads to size the connection mechanism. Section 6-3 presents the implementation of the tool. Then, the verification of the tool is presented in section 6-4.

6-1 Loads acting on the fuselage

The first subsection presents the different load cases. Next, the pressurization loads are considered. Finally, the inertial loads are taken into account. The Safety Factor (SF) used in the analysis is 8.

6-1-1 Load cases

In this present conceptual design analysis, only a limited amount of load cases are considered. They are based on steady-state maneuvering loads during cruise and hard landing. The nine load cases presented in table 6-1 are a variation of the aircraft weight, load factor, differential pressure and fuel mass. The limit load case for the cruise phase occurs with the aircraft at the MTOM and maximum load factor (2.5G). For the landing phase, the limit case occurs at the aircraft at Design Landing Mass $[kg]$ (DLM) and the hard landing load factor (-3.8G).

Load case	Aircraft weight	Differential pressure	Load factor	Fuel weight
1	Max payload	Max	Max	Max
2	Max payload	Max	Max	Min
3	Max payload	Max	Min	Max
4	Max payload	Max	Min	Min
5	Max payload	0	Max	Max
6	Max payload	0	Max	Min
7	Max payload	0	Min	Max
8	Max payload	0	Min	Min
9	DLM	0	Landing	Min

Table 6-1: The 9 load cases covering cruise and hard landing.

All the aircraft components are connected in some way to the fuselage. During the flight the air applies pressure on the component's surface which results in a force. During steady-state flight, all those forces are equal to the aircraft's weight and thrust. But since the point of action of those forces are not equal, bending occurs. Those aerodynamic loads are not taken into account. Neither are the torsional loads caused by the tail surfaces.

6-1-2 Pressurization loads

The load caused by the pressurization of the cabin is calculated using equilibrium of forces. Figure 6-1 shows the longitudinal loads and pressure load acting on the fuselage. The loads are given by the following equation:

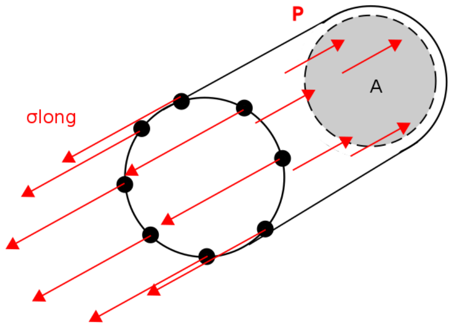


Figure 6-1: Longitudinal stress on bolts due to pressure.

$$\sigma_{long} = \frac{F * SF}{A_{bolts}} \tag{6-1}$$

Where:

σ_{long} = Stress in the longitudinal direction
F = Force exerted on the ends of the fuselage ($F = \Delta p * A_{enclosed}$)
SF = Safety factor
A_{bolts} = Surface area of all the bolts

6-1-3 Inertial loads

The inertial loads are caused by the fuselage itself and the parts connected to it. The fuselage itself includes the fuselage empty weight, the passenger weight and the cargo weight. They are all considered to be evenly distributed on the fuselage length. The components connected to the fuselage taken into account are: the engines, the main landing gear, the fuel tanks and the lifting surfaces (the main wing, horizontal stabilizers and vertical stabilizer) This is illustrated by figure 6-2. The lift is located in the middle of the fuselage to have no moment acting on the modelized fuselage.

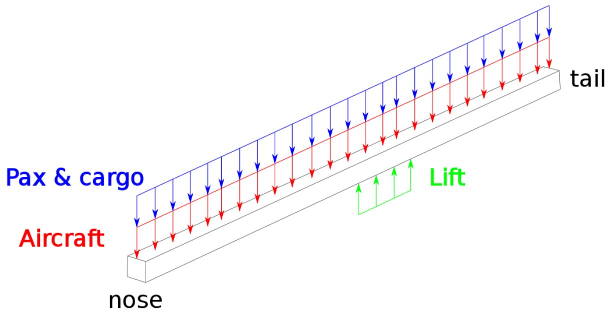


Figure 6-2: Loads acting on the fuselage idealized as a beam.

Longitudinal bending of the fuselage

This distributed load causes a moment carried by the normal stress of the bolts. Using beam theory, the normal stress to the section can be calculated using equation 6-2.

$$N_b = \frac{M * y * SF}{I_{section}} \tag{6-2}$$

Where:

N_{long} = is the stress normal to the section (axial load)
M = Moment
y = Vertical distance form the section centroid
$I_{section}$ = is the moment of inertia of the section

This axial stress has to be added to the one caused by the pressurization from subsection 6-1-2.

Shear occurring in the fuselage

The loads depicted above in figure 6-2 also cause shear in all the fuselage sections. The shear flow is given by:

$$q = q_0 - \frac{S * SF}{I_{shear}} Q \tag{6-3}$$

Where:

$$Q = \int z dA = \int z \bar{t} ds = \int r^2 \bar{t} \cos \alpha d\alpha \tag{6-4}$$

In these equations,

S = Shear stress acting on the section
z = Distance from the neutral axis to a point of interest
Q = First moment of area about the neutral axis
r = Radius of the fuselage
α = Angle as given on figure 6-3

The beams are numbered from 1 to 16, starting at the top with number 1 then increasing in the clockwise direction as given on figure 6-3.

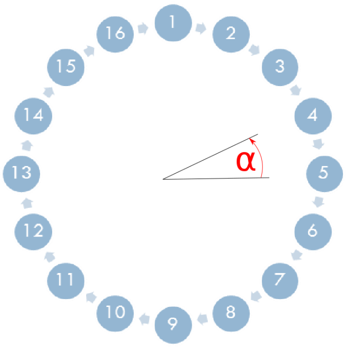


Figure 6-3: Beams numbering and angle definition.

Because of the symmetry of the section, the shear flow at the top and bottom booms are 0. By starting at the second boom the $q_0 = 0$ is already known. Then the other shear flows can be computed. They have a parabolic shape where the highest shear flow occurs at the neutral axis.

6-1-4 Total load acting on the fuselage

The connection bolts have to withstand both axial and shear loads. The axial loads in the bolts are caused on one hand by the pressurization of the fuselage (all bolts are loaded in tension) and on the other hand by the longitudinal bending moment of the fuselage (the bolts above the neutral axis [1-4, 14-16] are loaded in tension and the bolts under the neutral axis [6-12] are loaded in compression during regular steady sate flight condition). The shear stress in the bolts comes the longitudinal bending of the fuselage. All the loads are summarized in figure 6-4.

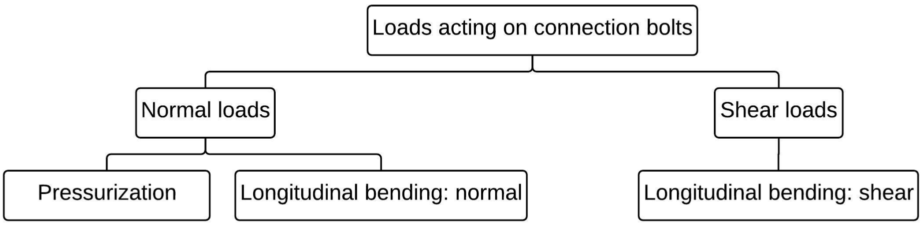


Figure 6-4: Components and origin of loads acting in the connection bolts.

6-2 Sizing the connection mechanism

6-2-1 Introduction

The goal of the sizing procedure presented in this section is estimating the weight of the connection mechanism between the fuselage parts. It is a physics-based weight estimation approach and therefore this section outline follows the steps of a structural design and analysis problem. The first step is starting with the idealization of the connection mechanism in subsection 6-2-2. The second step is defining the material used in subsection 6-2-3. Then, by using the results of the loads calculated in section 6-1 the structural sizing is presented in subsection 6-2-4.

Thanks to the loads analysis, the locations best suited to accommodate the connection mechanism are at the front, just behind the cockpit and at the back, just before the pressure bulkhead.

Using two-dimensional structural analysis, the size of the connection mechanism idealized as bolts can be calculated. Then the structural mass penalty is calculated.

6-2-2 Connection mechanism idealization

The connection mechanism is idealized as bolts connecting the frames as depicted in figure 6-5.

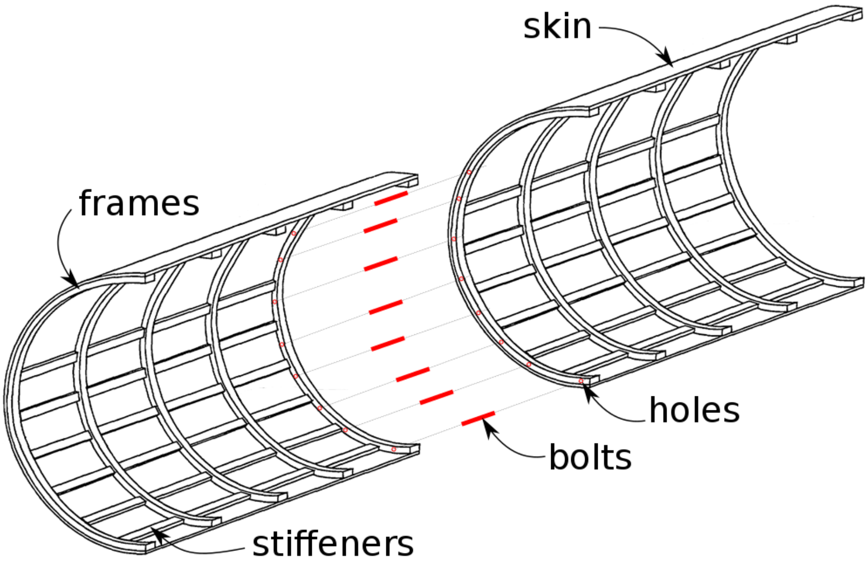


Figure 6-5: Connection mechanism idealized as bolts connecting the frames. (based on [72])

6-2-3 Material and fatigue for the connection mechanism

The materials used have a major impact on the weight of the structure. The Initiator design tool as well as this structural analysis assumes isotropic material which means that the material has the same properties in all directions, which is the case for metals but not for composite materials.

Another factor influencing the weight of a fuselage is its lifetime. The longer the lifetime, the more flight cycles and flight hours the fuselage will have endured over its lifetime. Those cyclic loads acting on the materials decrease its strength and this phenomena is called fatigue.

Fatigue is considered by selecting the design yield stress. It is the maximum stress that the part can take with no plastic deformation within a specified lifetime. For fuselage design, the most important factor determining its lifetime is the number of flights. Because it represents the number of pressurization-pressurization cycles done by the aircraft which causes some of the most important stresses in the fuselage. All the complex loads with different frequencies and amplitude applied to the fuselage during a flight are considered to be overred by one cycle. The aircraft should be able to withstand all the loads during its lifetime and start to plastically deform after.

Fatigue cycles are characterized by the cyclic stress ratio (r) and the cyclic stress amplitude (A) expressed as follows:

$$R = \frac{\sigma_{min}}{\sigma_{max}} \approx \frac{0}{\sigma_{max}} = 0 \tag{6-5}$$

$$A = \frac{1-R}{1+R} = \frac{1-0}{1+0} = 1 \tag{6-6}$$

Where the maximum and minimum stress are given by σ_{max} and σ_{min} respectively.

The reduction in material ultimate and yield stress caused by fatigue is illustrated for the aluminum alloy Al2024T3 (Alclad) in figure 6-6. To determine the design yield stress, it is assumed that the ratio $\sigma_{ultimate}/\sigma_{yield}$ is constant during the cyclic loading.

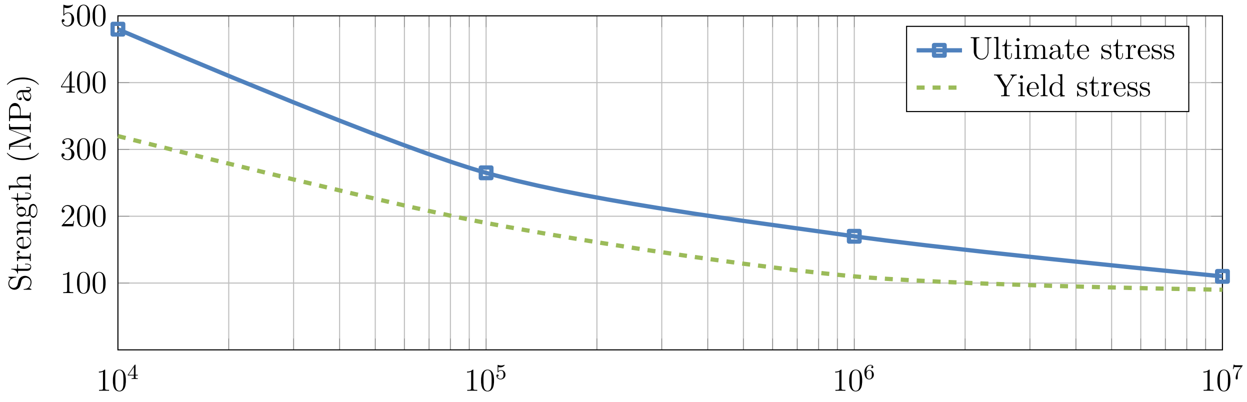


Figure 6-6: Ultimate and yield strength as a function of cyclic loadings (R = 0, A = 1) for the aluminum alloy Al2024T3 [73]

The goal of considering fatigue is to adjust the yield strength of the material for the sizing, according to the expected life of 50,000 cycles.

6-2-4 Structural sizing of the connection mechanism

The goal is to minimize the structural weight of the connection mechanism. This is done by determining the stresses acting in the bolts and their failure modes.

The axial stresses in the bolts are caused by the pressurization of the cabin and the longitudinal bending moment over the fuselage:

$$\sigma_{normal} = \frac{F * SF}{A} + \frac{M * y * SF}{I} \tag{6-7}$$

The shear due to the payload and fuselage mass must be carried by the bolts. They fail when the shear force reaches the material's shear strength.

For the normal loads, it is estimated that failure occurs when the σ_{normal} reaches the tensile yield stress (σ_y) or compressive yield strength of the material. For the shear loads, failure occurs when the shear strength of the material is reached. Both are decreased according to figure 6-6 for 50,000 cycles.

The sizing is done by minimizing the area of the bolts in order to respect the previous constraints.

6-3 Model implementation and user manual

This design tool can be run independently from any other program. It has 3 parts:

- Loads: defines the loads occurring in the bolts
- Sizing: this optimization procedure sizes the area of the bolts
- Mass penalty: this last part determines the weight of the connection mechanism

The activity diagram of this structural analysis tool is given in figure 6-7.

The user only has to enter some aircraft and calculation parameters. Then, the tool computes the stresses, sizes the bolts and displays the mass penalty for every individual connection system. The run time is less than a second.

6-4 Verification

The estimation of the forces acting on the bolts is discussed from a theoretical approach for the short aircraft under the first load case (the other load cases are taken into account by the tool) which is the most restrictive (maximum mass, load factor and pressure). The connection presented is the one just behind the cockpit.

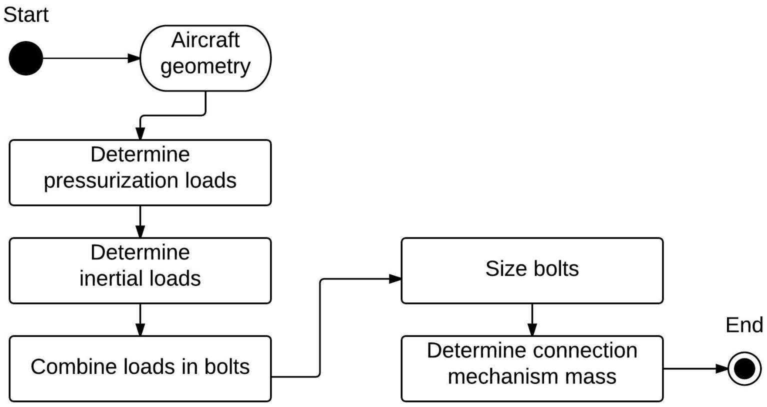


Figure 6-7: Activity diagram of the structural analysis tool

The pressurization of the cabin causes longitudinal stress that can be readily calculated according to equation 6-1 reproduced hereunder:

$$\sigma_{long} = \frac{F * SF}{A_{bolts}}$$

This is the larges tensile load on the bolts. Then comes the tensile load (for the bolts above the neutral-axis) caused by the bending moment of the fuselage according to equation 6-2 repeated hereunder:

$$N_b = \frac{My}{I_{setion}}$$

The moment M depends on the position on the fuselage. Indeed, the distributed load, shear and moment diagrams are given in figure 6-8 to 6-10. As it can be see, the wing introduces a sharp jump in the moment line. This equilibrates the fuselage in cruise condition.

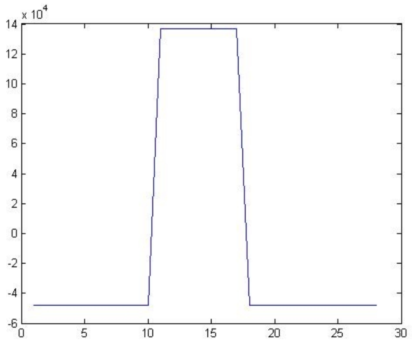


Figure 6-8: Distributed load along the fuselage

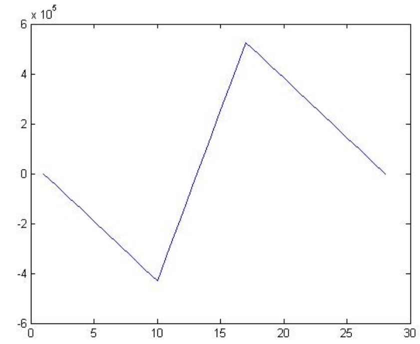


Figure 6-9: Shear load along the fuselage

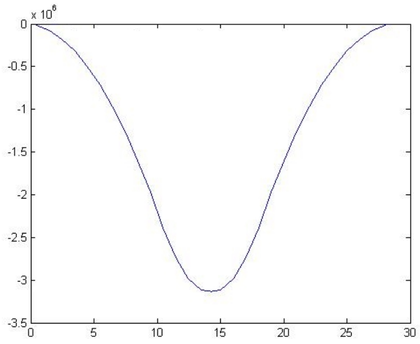


Figure 6-10: Moment load along the fuselage

The vertical shear load is known from figure 6-9 (260 kN) and can be applied on the structure. Using equation 6-3 reproduced hereunder:

$$q = q_0 - \frac{S}{I_{shear}} Q$$

Where $Q = \int z dA = \int z \bar{t} ds = \int r^2 \bar{t} \cos \alpha d\alpha$.

Chapter 7

Case studies & discussion

This chapter is divided in three parts. Section 7-1 computes the mass penalty. Section 7-2 studies the profitability of the concept. Finally, section 7-3 reflects on the findings.

7-1 Structural feasibility

The goal of this structural analysis is to determine the mass penalty of the connection mechanism on the long and short versions of the modular aircraft.

7-1-1 Case definition

The selected modular aircraft is of the 100-150 passengers category. As presented in chapter 5, the short version (or low-season version) of the modular aircraft seats 100 passengers and the lengthened version (or high season version) seats 150 passengers.

The transformation occurs by increasing the length of the fuselage with two plugs, one near the cockpit and one near the tail. This locations are better than the alternatives (just in front and after the wing) since the shear and moment loads calculation shown in chapter 6, figures 6-9 and 6-10 indicate much smaller loads at the extremities which allows for lighter connection mechanism.

The connection mechanism made out of bolts is idealized as booms. It means that only the booms are carrying direct stress. Also all the booms have the same area. The reason is because it would be very unpractical to have unique bolts for every location around the fuselage. It be against the principle of modularity at hand in this study. As a result, the section is doubly symmetric which means: $I_{yz} = 0$.

7-1-2 Geometry definition

The optimization procedure starts with an initial guess for the are of the bolts. Then the computations are performed and are explained in the following subsections. Then, after the optimization process, the total area of the booms for every connections are found and displayed in figure 7-1. As it can be seen, there are 4 different locations for the connection mechanism (A,B,C and D) and also two cases to consider: the short and long version. To keep the case study simple to follow, the results are explained step by step for the short version for location A only. The other results follow the same methodology and their resulting mass penalties are presented at the end of this section.

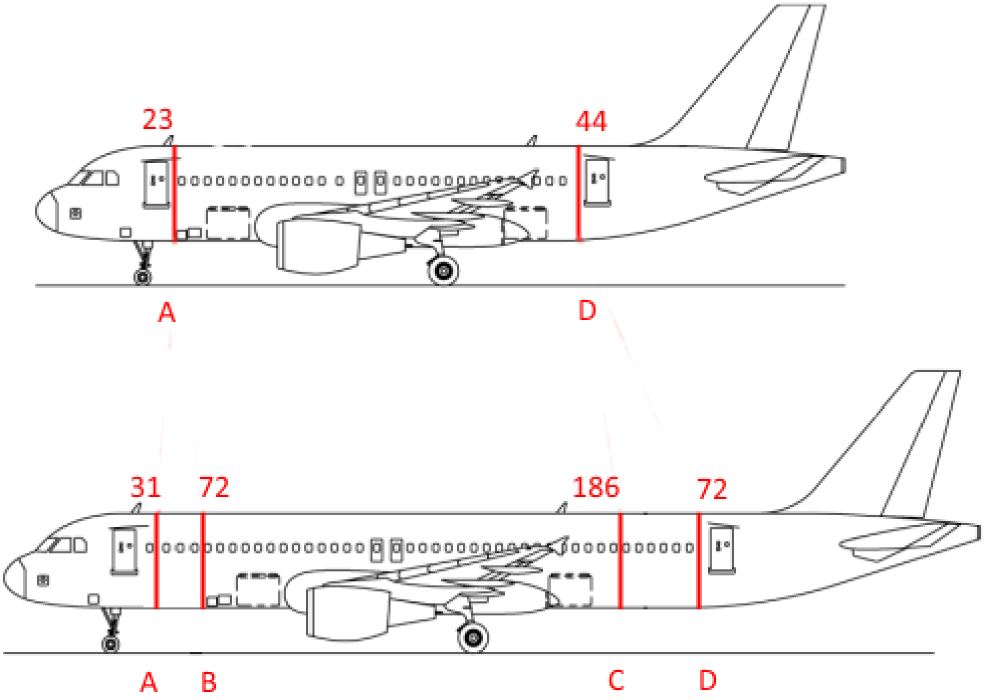


Figure 7-1: Location and required individual bolts area (in cm^2).

The connection mechanism is idealized as 16 bolts with the same area. Also, the radius of the fuselage is 2.05m. This gives enough information for the first step of sizing the bolts by calculating the I_{xx}:

$$I_{xx} = \sum_i A_i y_i^2 = 0.0023*(2*2.05^2+4*1.894^2+4*1.4496^2+4*0.7845^2) = 0.0769m^4 \quad (7\text{-}1)$$

7-1-3 Pressure loads

Recalling the load cases presented in table 6-1, the first four ones have maximum pressure differences applied to the fuselage and the last five load cases have no pressure loads. The force created due to the difference of pressure is given by:

$$F = \Delta p * A_{enclosed} = 62052 * \pi * 2.05^2 = 8.1924 * 10^5 N \tag{7-2}$$

The stress caused by the pressure load is:

$$\sigma_{duetopressure} = \frac{F * SF}{A_{bolts}} = \frac{8.1924 * 10^5 * 8}{0.0366} = 179.08 MPa \tag{7-3}$$

This is constant for all the bolts since they all have the same area.

7-1-4 Moment loads

The other component acting normally toe the bolts are the loads caused by the moment. They vary for every one of the 9 load cases. Hereunder is the normal stress for the maximum load cases (load case 1 and 5) computed for the 16 bolts:

$$N_{1-16} = \frac{M * y_{1-16} * SF}{I_{xx}} = \frac{3.8958 * 10^5 * y_{1-16} * 8}{0.0769} \tag{7-4}$$

$$N_1 = \frac{2.153 * 10^5 * 2.05 * 8}{0.0769} = 45.92 MPa$$

$$N_{2,16} = \frac{2.153 * 10^5 * 1.894 * 8}{0.0769} = 42.42 MPa$$

$$N_{3,15} = \frac{2.153 * 10^5 * 1.4496 * 8}{0.0769} = 32.47 MPa$$

$$N_{4,14} = \frac{2.153 * 10^5 * 0.7845 * 8}{0.0769} = 17.57 MPa$$

$$N_{5,13} = \frac{2.153 * 10^5 * 0 * 8}{0.0769} = 0 MPa$$

$$N_{6,12} = \frac{2.153 * 10^5 * -0.7845 * 8}{0.0769} = -17.57 MPa$$

$$N_{7,11} = \frac{2.153 * 10^5 * -1.4496 * 8}{0.0769} = -32.47 MPa$$

$$N_{8,10} = \frac{2.153 * 10^5 * -1.8940 * 8}{0.0769} = -42.42 MPa$$

$$N_9 = \frac{2.153 * 10^5 * -2.0500 * 8}{0.0769} = -45.92 MPa$$

The moment loads for the other load cases are smaller.

7-1-5 Shear loads

The shear flow distribution in the connection mechanism is basically the analysis of an idealized single cell closed section beam. It is assumed that the skin carries no direct stress, as a result, the shear flow distribution is given by equation 7-5:

$$qs = -(\frac{S_x I_{xx} - S_y I_{xy}}{I_{xx} I_{xy} - I_{xy}^2}) \sum_{r=1}^{n} B_r y_r - (\frac{S_y I_{yy} - S_x I_{xy}}{I_{xx} I_{xy} - I_{xy}^2}) \sum_{r=1}^{n} B_r x_r + q_{s,0} \tag{7-5}$$

Since there is only a vertical load ($S_x = 0$) and the structure is symmetric ($I_{xy} = 0$), equation 7-5 reduces to (where the Safey Factor has been included):

$$qs = -\frac{S_y * SF}{I_{xx}} \sum_{r=1}^{n} B_r y_r + q_{s,0} \tag{7-6}$$

The vertical load S_y has been calculated for the nine load cases and the maximum is the one occurring for load cases 1 and 5: $-2.5972 * 10^5 N$. Since $I_{xx} = 0.1768 m^4$ as before, Then,

$$q_s = \frac{-1.4353 * 10^5 * 8}{0.0809} \sum_{r=1}^{n} B_r y_r + q_{s,0} \tag{7-7}$$

As it can be seen in equation 7-7, q_b is the sum of two terms. The first term is the "open section" shear flow q_b. To compute them, one of the skin panels is "cut", in this case panel 1-2. The results are displayed in table 7-1. To find $q_{s,0}$, the moment around the center is taken using the following equation:

$$M = \oint p q_b \, \mathrm{d}\ s + 2A q_{s,0} \tag{7-8}$$

Since the moment is 0 because the shear force acts in the shear center and there is no torsional loads:

$$0 = -2A_{12} q_{b,12} - 2A_{23} q_{b,23} - ... - 2A_{161} q_{b,161} - +2A q_{s,0} \tag{7-9}$$

Where $A_{12}, A_{23}, ..., A_{161}$ are the areas subtended by the skin panels 12, 23,...,161 at the center of the cross section.This is equal to one 16^{th} of the area enclosed: $A_{enclosed}/16 = 13.2025/16 = 0.8252 m^2$. And the sum of all the $q_b = -5.6012 * 10^5 N/m$. Substituting these values give:

$$q_{s,0} = 3.5007 * 10^4 N/m \text{ (acting in the counter-clockwise direction)} \tag{7-10}$$

Adding $q_{b,open}$ and $q_{s,0}$ together give the final shear flow represented in figure 7-2. These shear flows are converted to shear stresses by dividing them by the smeared thickness defined as:

$$t_{smeared} = \frac{A_{bolts}}{2 * \pi * R_{fuselage}} = \frac{16 * 0.0023}{12.8805} = \frac{0.0366}{12.8805} = 0.0028 m \tag{7-11}$$

The shear stress in the 16 bolts are then given by:

$$\tau = \frac{q_b}{t_{smeared}} \tag{7-12}$$

The values can be found in figure 7-3.

Skin panel starting at boom	$B_r(m^2)$	$y_r(m)$	$qb(N/m)$
1	0.0024	2.05	0
2	0.0024	1.89	64690
3	0.0024	1.44	114190
4	0.0024	0.78	140990
5	0.0024	0	140990
6	0.0024	-0.78	114190
7	0.0024	-1.445	64690
8	0.0024	-1.89	0
9	0.0024	-2.05	-70020
10	0.0024	-1.89	-134700
11	0.0024	-1.45	-184210
12	0.0024	-0.78	-211000
13	0.0024	0	-211000
14	0.0024	0.78	-184210
15	0.0024	1.45	-134700
16	0.0024	1.89	-70020

Table 7-1: Open section q_b results

7-1-6 Load analysis per bolt

All the bolts are subjected to shear stress and normal stress, which can be positive (tension) or negative (compression). In this section, the loading of the bolts are compared to their limit loads. Every bolt is analyzed individually and the maximum tensile, compressive and shear stresses of all the loading cases are summarized in figure 7-3. As it can be seen, the most restrictive constraint is the tensile stress of bolt 1 (at the top of the fuselage). That one is stressed at 100%. It occurs for load cases 1 and 5. Those stresses include the safety factor of 8 from the forces and moments acting on the fuselage.

7-1-7 Resulting mass penalty

The optimization procedure described in the previous subsection has been carried out for locations A, B, C, D and both sizes of the modular aircraft. The mass penalty of all the connection mechanisms are summarized in figure 7-4:

As a result, the total mass penalty for both the short and long version of the modular aircraft are summarized in table 7-2 and compared to their respective fuselage masses.

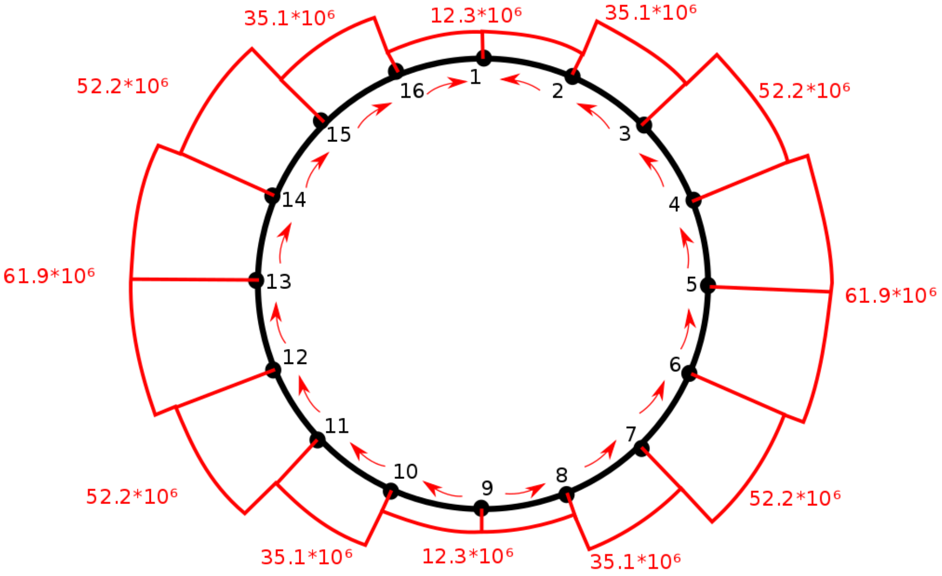
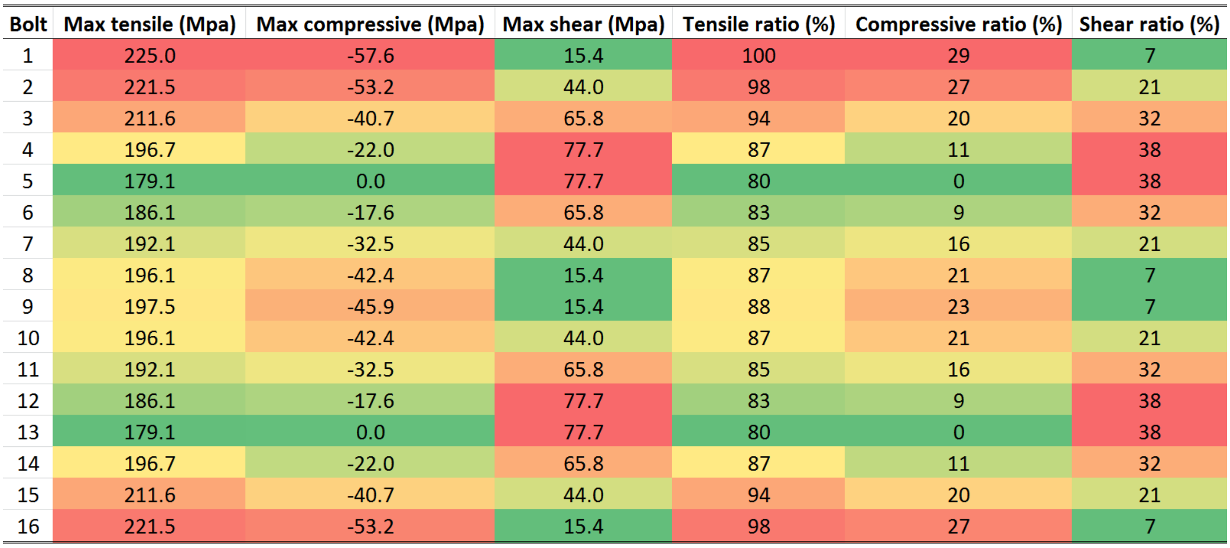


Figure 7-2: Shear flow distribution

Version	Mass Penalty (kg)	$M_{fuselage}$ (kg)	Mass Penalty (% of $M_{fuselage}$)
Short	86	5600	1.5
Long	467	8400	5.6

Table 7-2: Total mass penalty for the modular aircraft



Bolt	Max tensile (Mpa)	Max compressive (Mpa)	Max shear (Mpa)	Tensile ratio (%)	Compressive ratio (%)	Shear ratio (%)
1	225.0	-57.6	15.4	100	29	7
2	221.5	-53.2	44.0	98	27	21
3	211.6	-40.7	65.8	94	20	32
4	196.7	-22.0	77.7	87	11	38
5	179.1	0.0	77.7	80	0	38
6	186.1	-17.6	65.8	83	9	32
7	192.1	-32.5	44.0	85	16	21
8	196.1	-42.4	15.4	87	21	7
9	197.5	-45.9	15.4	88	23	7
10	196.1	-42.4	44.0	87	21	21
11	192.1	-32.5	65.8	85	16	32
12	186.1	-17.6	77.7	83	9	38
13	179.1	0.0	77.7	80	0	38
14	196.7	-22.0	65.8	87	11	32
15	211.6	-40.7	44.0	94	20	21
16	221.5	-53.2	15.4	98	27	7

Figure 7-3: Maximum loading of all the bolts

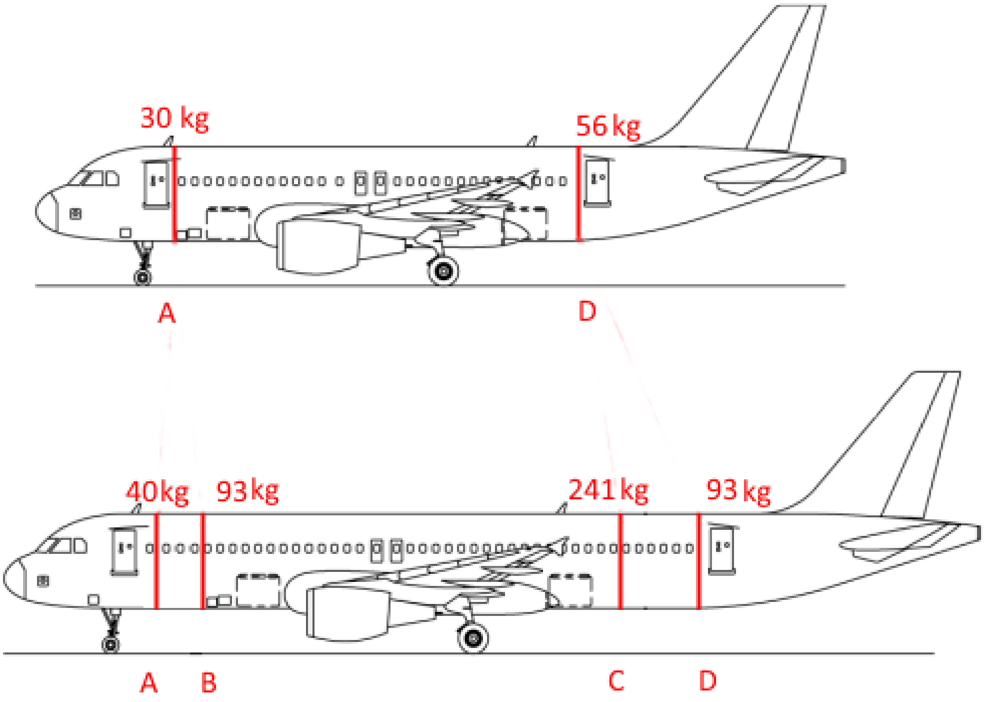


Figure 7-4: Mass penalty of the connection mechanisms (in kg)

7-2 Economical feasibility

The subject of the economical analysis is the aircraft operators. The analysis is performed in two steps. The goal of the first step is to asses the profitability of the modular aircraft compared to an optimal aircraft. The second step is designed to compare a fleet of modular aircraft to a fleet of standard aircraft in a network.

7-2-1 Case 1: aircraft analysis

Case definition and methodology

The financial analysis compares the profitability of the modular aircraft to the optimal equivalents on one precise route. The chosen flight leg is 4800km (=2592nm) long with a demand of 60,000 passengers per year. This corresponds to around 9h of flights per day, which is in accordance to the numbers reported by the IATA. The following two comparisons are going to be done:

- the short modular aircraft (100 seats) ⇔ optimal small aircraft (100 seats)
- the long modular aircraft (150 seats) ⇔ optimal large aircraft (150 seats)

Both modular aircraft carry the mass penalty calculated in chapter 6 which is 86 kg and 467 kg for the short and long version respectively.

The Initiator design tool has a financial module able to calculate the revenues, costs and profits for different aircraft type. The profits are equal to the revenues minus the costs, interests and tax; as described hereunder in figure 7-5. The four components of profits are presented in table 7-3.

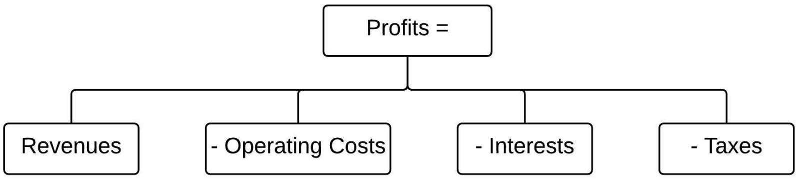


Figure 7-5: Composition of profits

The calculation of the revenues is quite straight forward as it can be seen in table 7-3. They are based on the yields of the economy and first class. But the calculation of the Total Operating Costs (TOC) are more complex. The costs estimation method first estimates an initial list price using regression analysis on a historical database. Then it computes

1. Revenues = Yield * Seats * Load Factor * Range * Nbr flights * (1+Inflation Rate)
    - (a) Yield = 0.14 $/nm/pax (Eco = 0.1 $/nm/pax, first class = 0.3 $/nm/pax)
    - (b) Seats = 100
    - (c) Load factor = 80 %
    - (d) Range = 2592 nm (=4800km)
    - (e) Nbr Fligths = 600 / year
    - (f) Inflation Rate = 2 %
2. Operating Costs = TOC * Range * (1+Inflation Rate)
    - (a) TOC = 23.2353 $/nm
3. Interests = Interest Rate * Book
    - (a) Book = AC List Price - Depreciation costs * Range
        - i. AC List Price = $57,4 * 10^6$ €
        - ii. Depreciation costs = DOCdepr * Dist per year
            - A. DOCdepr = 3.5465
            - B. Dist per year = 1554850nm
4. Taxes = = TaxRate * (Revenues - Total Operating Costs - Interests)
    - (a) TaxRate = 3%

Table 7-3: Breakdown of the profits calculation in The Initiator the Non-Recurring Costs (NRC). The operating costs are then computed. The breakdown of the TOC used in The Initiator is shown in figure 7-6. The result is the TOC of the aircraft expressed in US$/nm. Finally, the profitability is converted to be expressed as profits/pax/flight as the IATA does in its reports. This is done over the course of 20 years and averaged out.

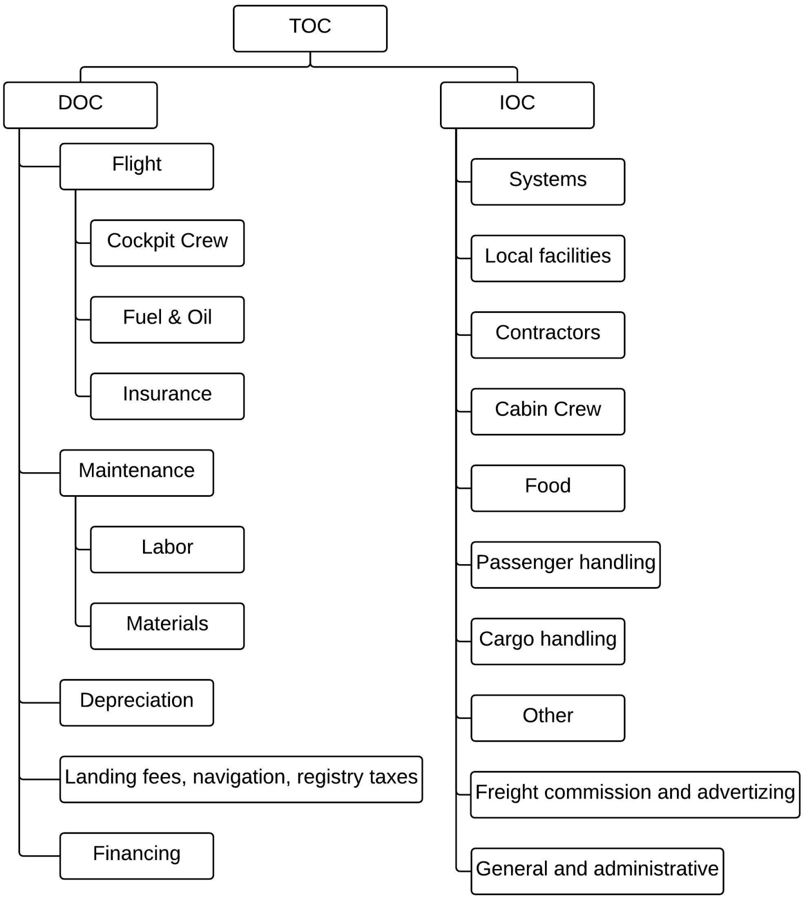


Figure 7-6: Breakdown of the total operating cost (according to [75] [76])

Impact of mass penalty on profitability

Figure 7-7 presents the impact of the mass penalty on the profitability of the modular aircraft. The dotted line (green) is a constant line indicating the profits ($/pax/flight) of the optimal aircraft carrying 100 passengers. It is a reference and does not vary with the mass penalty. The blue line displays the impact of the mass penalty on the profits of the modular aircraft (100 pax as well). Both are computed with a load factor of 80%. First of all, as it can be seen, neither aircraft generate a profit. This is due to the realistic

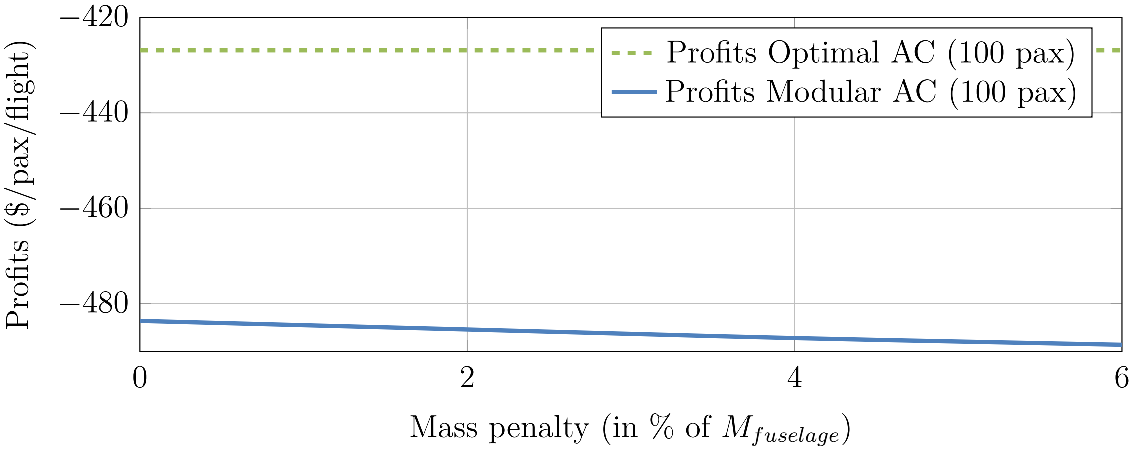


Figure 7-7: Comparison of profitability between optimal and Modular 100 passenger aircraft.

yields used and slight over estimation of the costs by the tool. The impact of increasing the yields to obtain profitable aircraft is investigated in the next subsubsection: sensitivity analysis. Secondly, the modular aircraft with the non-optimal wing, largely under performs compared to the optimal aircraft. Finally, the increment in mass penalty has little impact compared to the non-optimal configuration.

A similar graph is displayed for the long version of the aircraft. Since the long aircraft serves as basis for the modular version, their profitability start at the same level. Then the reference stays constant for the optimal version (green dotted line), and the modular aircraft's profitability decreases with the increasing mass penalty as it can be seen with the blue line in figure 7-8. Both are computed with a load factor of 80%.

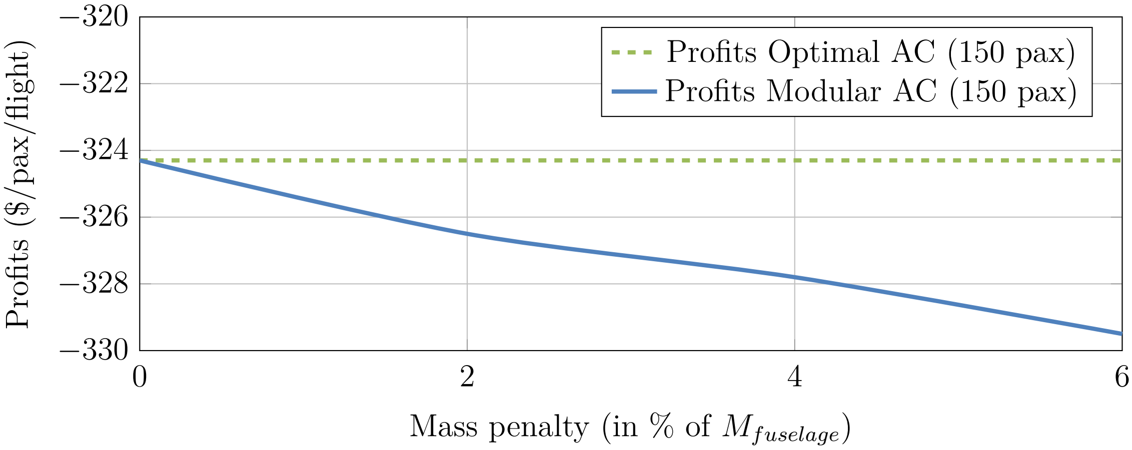


Figure 7-8: Comparison of profitability between optimal and Modular 150 passenger aircraft.

It can clearly be seen that the impact of the mass penalty is relatively small.

Impact of load factor

As it can be seen previously, the modular aircraft performs much worse than the optimal aircraft. So the question is now: which improvement in load factor should be achieved in order to outweigh the penalizing design of the modular aircraft. To answer this question, the following two figure present the profits per passenger per flight versus the load factor for both the short and long version of the modular aircraft.

Again, the dotted line (green) is a constant line indicating the profits ($/pax/flight) of the optimal aircraft carrying 100 passengers with a load factor of 80%. It is a reference and does not vary over the x-axis. The blue line displays the impact of the load factor on the profits of the equivalent modular aircraft with a mass penalty of 2% of the fuselage mass, as computed previously.

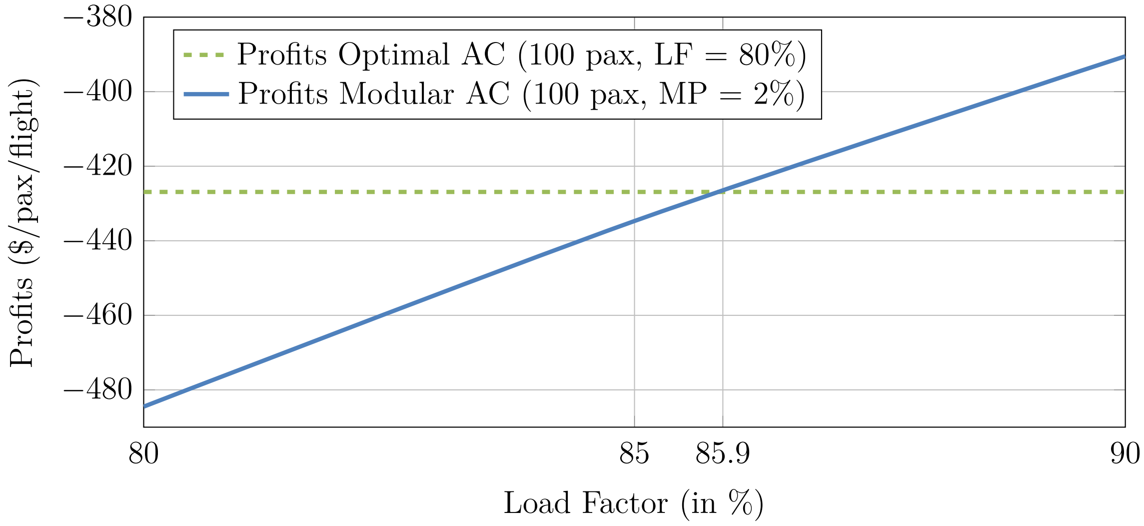


Figure 7-9: Required improvement in load factor for the short aircraft

As it can be seen in figure 7-9, the break-even load factor for the short modular aircraft is 85,9% The meaning of this is going to be discussed in section 7-3.

A similar graph can be made for the long version of the modular aircraft compared to the optimal aircraft carrying 150 passengers as well, it is displayed in figure 7-10. As it can be seen, the long version of the modular aircraft starts almost at the same profitability level as the optimal aircraft. This is because the mass penalty is only 6% of the fuselage mass as computed previously. Then the profitability increases tremendously with the increasing load factor. For the long aircraft, the break-even point occurs already at 80,7%.

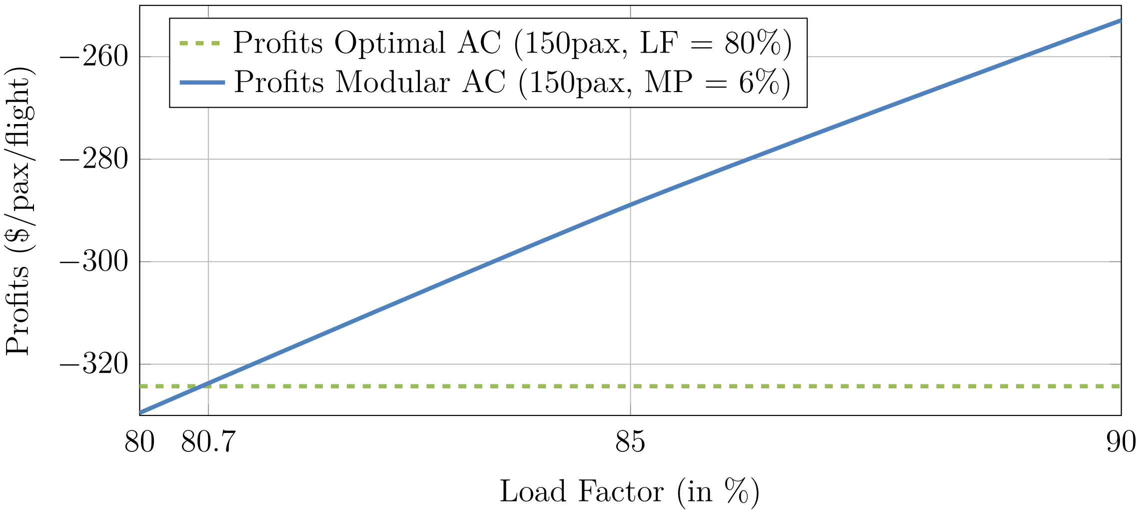


Figure 7-10: Required improvement in load factor for the short aircraft

Sensitivity analysis

The previous four graphs show that the aircraft generate loss instead of profit. The goal is to study again the effect of mass penalty and load factor on the profitability of the aircraft but this time by using new yields. To determine if this negative revenue influence this analysis, the yields are increased according to table 7-4.

Class	**Standard Yield ($/pax/nm)**	**Increased Yield ($/pax/nm)**
Economy	0.1	0.205
First	0.3	0.615

Table 7-4: Yields for the sensitivity analysis

Those yields have been chosen because this leads precisely to a 7$ profit per flight as reported by the IATA [6].

The profitability of the short modular aircraft is compared to the optimal aircraft carrying 100 passenger as well in figure. The dotted line (green) is a constant line representing the reference 7$ profit. It is a reference and does not vary over the x-axis. The blue line displays the impact of the mass penalty on the profits of the modular aircraft (100 passengers as well).

Again, as it can be seen in figure 7-11, the profitability of the short version is substantially lower than the reference 7$. The reason is because the non optimal wing plays a very penalizing effect on the performances. Subsequently, it can be seen that the profitability is only slightly influenced by the mass penalty.

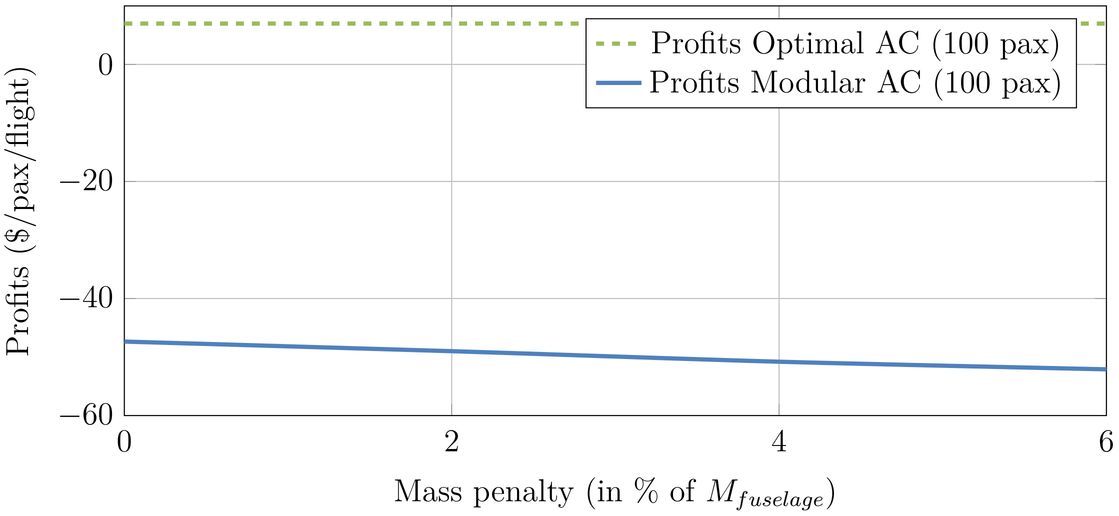


Figure 7-11: Impact of yield on the short version.

A similar graph can be made for the long version of the modular aircraft as displayed in figure 7-12.

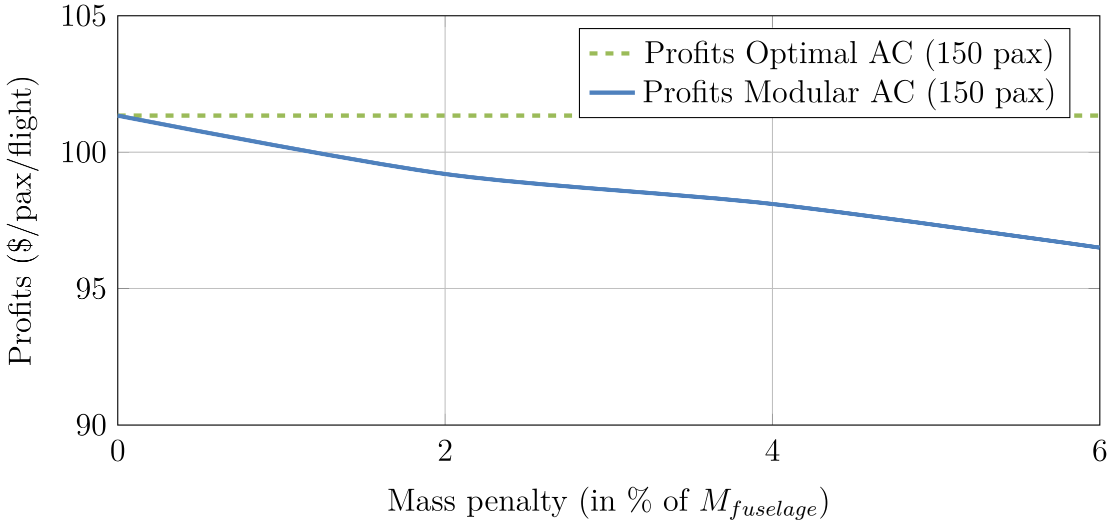


Figure 7-12: Impact of yield on the long version.

As it can be seen, the increased yields means a massive increase in the profits to around 100$. However, the revenues are still only slightly affected by the increase in mass penalty.

The analysis of the break even points with larger yields is done in the following two figures.

Figure 7-13 shows the reference line of the short optimal aircraft in green. It is constant and does not vary with the load factor. The blue line displays the profit of the short modular aircraft. As it can be seen in figure 7-13, the break even point occurs already at 82,7% instead of the 85,9% with lower yields as displayed earlier in figure 7-9.

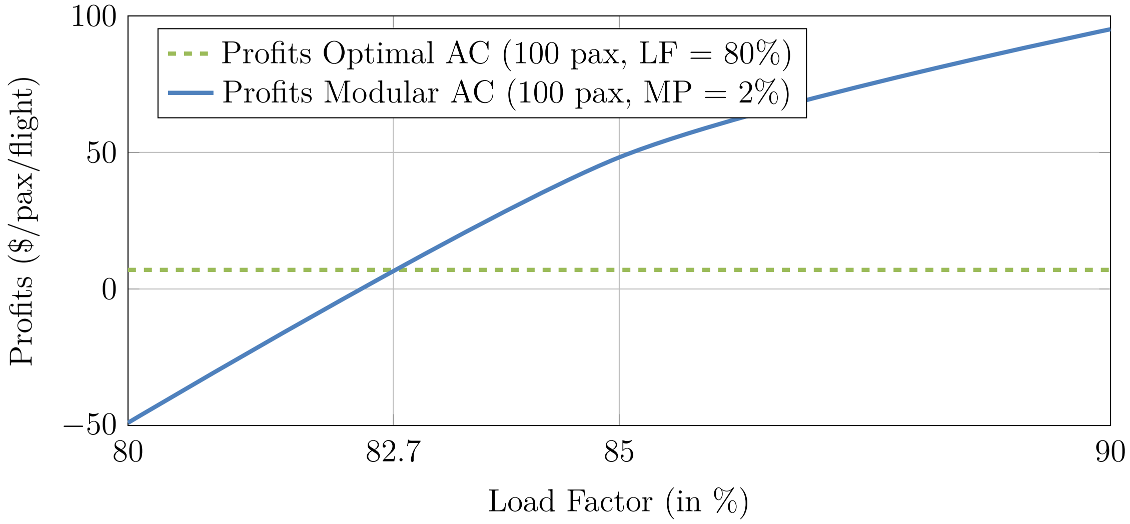


Figure 7-13: Required improvement in load factor for the short aircraft with larger yields

A similar graph is displayed for the long version in figure. Figure 7-14 shows that a larger yield has almost no impact on the break even point changing from 80,7% to 80,6%.

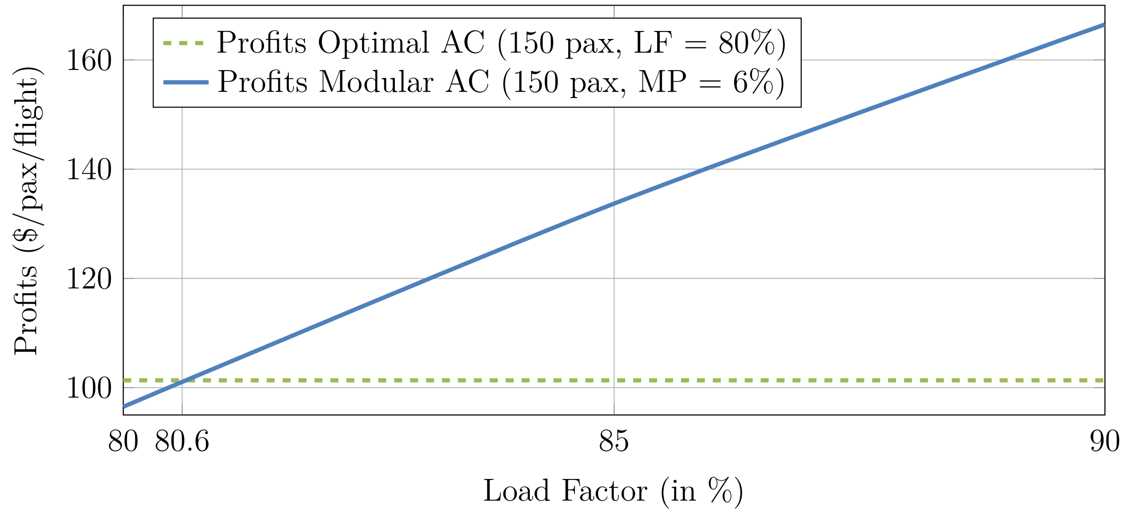


Figure 7-14: Required improvement in load factor for the short aircraft with larger yields

7-2-2 Case 2: airline analysis

In this second step, the first tool to design a family of aircraft is used to set a reference profit for a network. Then the same network is flown with the modular aircraft. In both cases the passenger demand varies over time according to the seasons as presented in chapter 1, figure 1-1.

Case definition

For this case, the load factors are 80% and the standard yields are used as displayed in table 7-5 .

Class	Standard Yield ($/pax/nm)
Economy	0.1
First	0.3

Table 7-5: Yields for the airline case

There are 4 routes, all doing 4800 km and requiring at least 10 flight per day. They have slightly different passenger demands but passenger demand variation respects the seasonal variation as displayed in chapter 1, figure 1-1. The modelized passenger demand is displayed in figure 7-15.

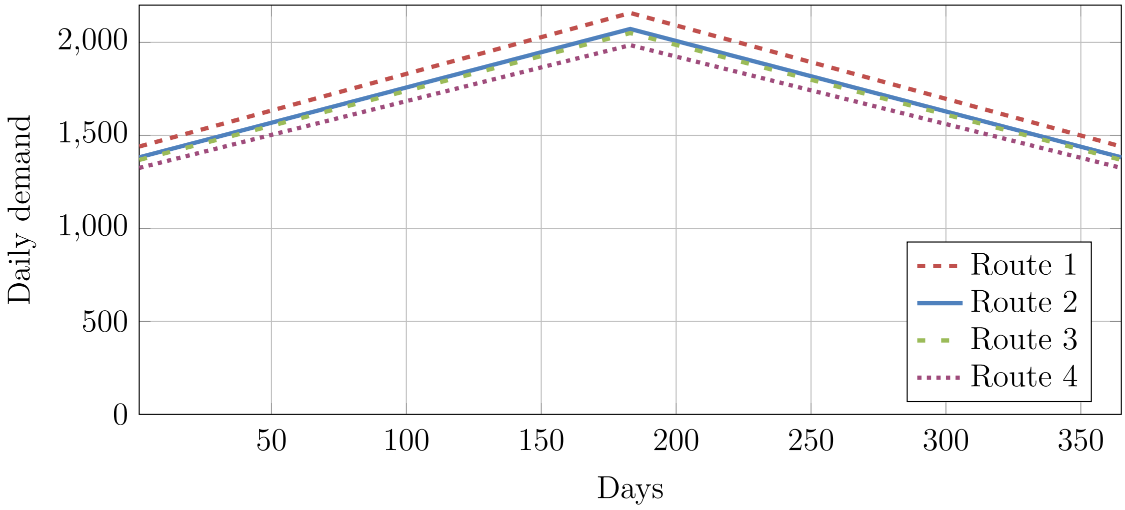


Figure 7-15: Passenger demand for the 4 routes

For convenience, the first day is defined as the day of lowest demand in the year.

Establishing a basis profit with the classical family fleet

According to this demand, the fleet is composed of one aircraft type of which some are bought and some are leased. The optimal size of the aircraft is 150 seats as it is related to the range. The required number of aircraft per destination per day is given in figure 7-16. The number of bought aircraft are the basis of the fleet. Then, regularly over the course of the year, aircraft are leased to answer the increase in demand. To determine the profits, the estimation from the Initiator is used. Those profits are valid for bought aircraft. But since some aircraft are leased, there is an intermediate party more whom also takes a margin for its own profit. According to the IATA, aircraft lessors make a profit margin of 9% [77]. As a result, it is assumed that the leased aircraft's profits are reduced by that percentage.

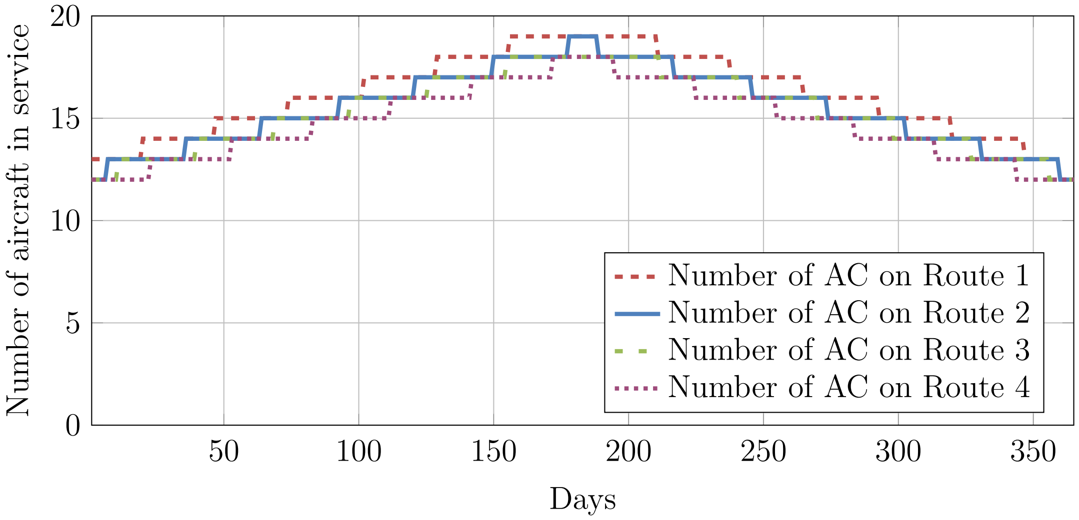


Figure 7-16: Number of aircraft assigned to the 4 routes.

Factoring in all this data and the spilled passenger demand that could not be answered of 51869 in total for one year, the standard family makes a loss of 1470,2 millions €/year. But as seen in the sensitivity analysis subsubsection above, it is a good basis for a comparison.

Profit by using the modular fleet

This time, the demand and the routes are the same as for the standard family fleet. But the aircraft are all modular. Starting in the short version in the low-season and increasing in size according to the demand.

Taking into account the different aircraft sizes and the much smaller spilled passengers demand of 25337 in total for one year, the modular fleet still makes a loss of 1782,3 million €/ year, which is considerably worse than the optimal family of aircraft.

7-3 Discussion

To summarize the findings, hereunder is an interesting table offering more insight in what is happening. Table 7-6 shows the total operating costs of the 4 aircraft in question.

Aircraft	TOC ($/pax/nm)
Optimal 100 pax	23.38
Modular 100 pax	25.13
Optimal 150 pax	31
Modular 150 pax	31.21

Table 7-6: TOC of the 4 aircraft

As it can be seen, the TOC are sensibly higher for the modular versions. Unfortunately this could not be mitigated by the increased number of passengers an airline can carry because it can fit better its offer to the demand.

To outweigh the cost penalty, the modular aircraft should be able to increase the load factor from 80% to 85.9% in the short version and 80.7% in the long version. Furthermore, when analyzing the airline with a fleet of modular aircraft it can be seen that the benefit of the modular aircraft of transporting more passenger cannot outweigh the cost penalty when keeping the load factor constant at 80%.

The risks associated with the modular aircraft should also be considered. First of all is the important aspect of conversion time: how much time is required to change the aircraft from one configuration to the other. For the purpose of this study, it is assumed that the conversion can be done together with normal maintenance. So there is no penalty of keeping the aircraft on the ground only to switch from one version to the other. Secondly, the certification of such a system is also going to cost time and money. Thirdly, the passenger acceptance is also an important factor. For instance, windowless aircraft are not commercialized at the moment only because no passenger would want to board such a plane. A similar fear from passengers about an aircraft that is designed to be opened and closed twice a year could spark some anxiety amongst the population.

Increasing the load factor to 85.9% is a tall order, especially when considering the alternative options to improve it. From a hardware perspective, simply leasing aircraft seems to be a good solution as it can be seen in the second case where the family fleet leases part of the aircraft. Another hardware alternative is adjusting the seat pitch. This could offer some seats with more leg room during the low season which could be sold for more. Of course performing the maintenance rather in the low-season than the hi-season is a good solution to naturally adapt the offer to the demand with a constant fleet. From a software perspective, the ticketing systems and demand prevision softwares are getting more and more accurate. This could allow for a better fleet planning. Then another trend that is very promising is real-time health management of the aircraft. This allows increases the reactivity of the maintenance by waiting at the destination of the aircraft with the correct part ready to replace or by improving the failures identification and applying adequately the corrective action. Then there is of course varying the price. This can be done for the same seat by changing the price over time according to the filling of the aircraft, rival promotions, events,... Or the price can change by offering different services for the same flight.

Chapter 8

Conclusions and Recommendations

8-1 Conclusions

The goal of this thesis was to find out if a modular concept of aircraft would be a good solution for coping with the seasonal variation of passenger demand. The motivation behind this research is the need for a more cost-effective and sustainable aircraft for which the modular aircraft could be a solution. The problem to overcome is quantifying the mass penalty associated with the connection mechanism and the impact it has on the profitability. This requires a basis profit reference to compare the modular aircraft to. Based on the research presented in the previous chapters, hereunder follow a number of conclusions.

Family design tool

The first part of the research is aimed at establishing a reference to compare the modular aircraft with. The idea is to create a tool able to design the optimal family of aircraft according to the input network and passenger demand. The user gives the range, daily passenger demand for every route and the maximum desired of different aircraft types. Then the tool uses mixed integer programming to find the solution. The tool works well for small networks up to around 8 destinations. Beyond that, the computing time becomes too long on regular computers.

Modular aircraft design tool

This tool is integrated in the Initiator and allows the design of modular aircraft. This is done by defining some pre-defined parts of an aircraft. For instance, the fuselage diameter can be constrained. Different engines can be mounted on particular aircraft. Mass penalties can be added to fuselages. The tail and wings can also be defined. This allow the creation of many different configurations. The best choice for the modular aircraft turns out to start from the long version. Then decrease the fuselage length, change the engines and the landing gear. As a result, both the long and short version of the modular aircraft share the same wing: the one from the large aircraft.

Mass penalty analysis

The mass penalty estimation is based on a simplified structural analysis. The connection mechanism is idealized as bolts spread over a single closed cell. Nine different load cases are considered in this study including steady state flight and hard landing. The most constraining load case is the one where the aircraft flies at its maximum load factor (g), MTOM and has maximum pressurization difference. The safety factor used is 8.

The model used is replacing the fuselage by a 1-dimensional beam on which the loads are acting. The loads are translated in moment and shear forces in the individual fuselage sections. The normal loads are made out of the bending moment and the axial tension caused by the pressurization of the fuselage. The shear force is carried by the bolts.

The sizing of the bolts is done with respect to the von Mises yield criterion which accounts for normal stresses and shear stress. The bolts all have the same area because it would be inconvenient to have unique bolts at every location during the conversion operation from one version to another.

The analysis tool requires only basic input to estimate the mass penalty of any aircraft.

Verification

The verification of the modular design tool is done in three ways. Firstly by analyzing the weight and dimensions of all the configurations. Secondly, by inspecting the geometry. Finally, by comparing the design points of the different configurations on the $T/W - W/S$ diagram. It turns out that the tool works perfectly and is able to make all the necessary configurations.

The validation of the structural analysis is performed from a theoretical case study. It turn out that the estimation is good for a conceptual level and allows for a correct profitability analysis.

Economical analysis

The economical analysis considers the aircraft themselves on one hand, and a fleet of modular aircraft on the other hand. The Initiator design tool has a module able to estimate the total cost of the aircraft together with the revenues and profits generated over 20 years. The costs estimation method first estimates an initial list price using regression analysis on a historical database. Then it computes the NRC. The operating costs are then computed. The revenues are based on the yields of the economy and first class. It turns out that the economical model predicts that the aircraft are making losses over their lifetime instead of profit. Therefore a sensitivity analysis is carried out by increasing the yields in order to obtain a profit of 7$ per flight. It tuns out that the model is robust and that negative returns can still be used for a comparison basis.

The first study cases analyses the impact of the mass penalty on the profitability. The modular aircraft's profitability is significantly lower than their optimal equivalent but the mass penalty has a very small effect. The profitability of the short version is particularly worse than the optimal aircraft . The reason is because the modular aircraft flies with the wing of the large version and this turns out to be the most important penalizing factor. Next, the required improvement in load factor necessary to outweigh the design penalty is calculated. The short version of the modular aircraft should have a load factor of 85.9% to reach the same level of profitability as the optimal aircraft. The long aircraft only needs an improvement of 0.9%.

The second study case compares the profitability of a modular fleet to a family fleet. For this, a passenger demand varying according to the seasons is modeled. The passenger demand vary linearly every day. Then the family fleet answers this demand by buying a basis of aircraft, then leasing extra aircraft to fulfill the increasing demand as soon it can fill an aircraft at 80%. This results in quite a large spill. Also, the leased aircraft generate 9% less profits compared to the bought aircraft since there is one intermediate party more taking its part of the cake. Then the profits generated by the family fleet are computed using the yield values from The Initiator.
Then, the same demand is answered with a fleet of modular aircraft. They increase in size as the demand increases. And even though the modular aircraft allow a reduction of the passenger spill by a factor 2, the modular fleet still under-performs compared to the optimal fleet.

It can be concluded that the present study adequately evaluates the potential of modular aircraft. The mass penalty has a small impact on the profitability compared to the non-optimal wing used by the short version. The nodular aircraft should improve the load factor to 85.9% during the low season. This is a risky endeavor for a small return. As a result, improving the utilization of optimal aircraft is a better alternative.

8-2 Recommendations

Family design tool The first improvement that could be done is increasing the design space by including all the possible aircraft instead of the optimal aircraft per input route. This is going to require a thorough study and new optimization procedure.

Computation time The family design tool works well but suffers from long computation time as soon as the network size increases beyond 8 routes. So reviewing the optimization procedure for speed can offer interesting benefits.

Modular aircraft design Improving the user interface or user experience to facilitate the experimentation could offer easier access to the tool. Because at the moment it can only work using a modified version of The Initiator code with the correct parameters names as described in the appendices.

Structural analysis It could be improved by including the aerodynamic and torsional loads in the analysis of the forces acting on the fuselage.

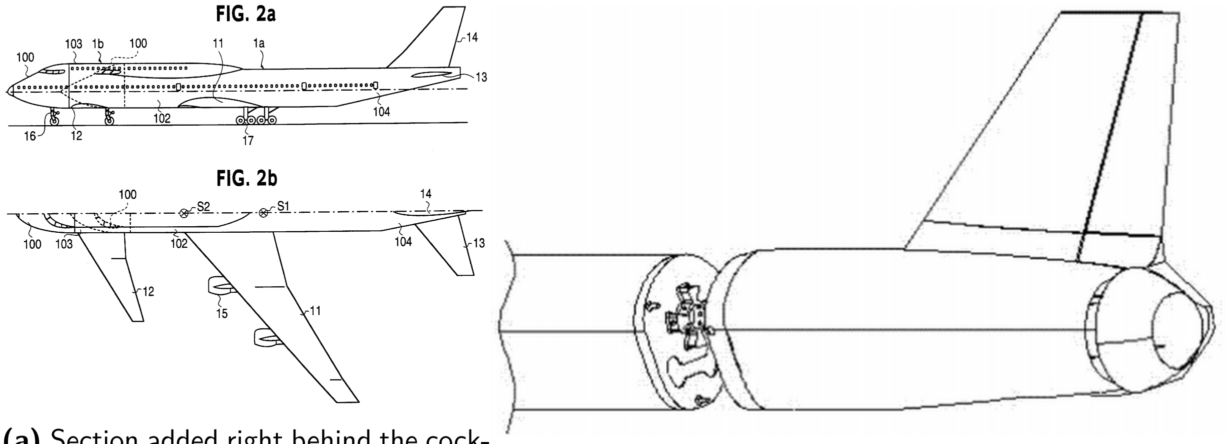
Modular aircraft profitability It could be improved by using commercially available softwares to allow for another analysis of the modular aircraft. It should be verified that those software can handle non-optimal aircraft.

Airline profitability Using the total operating costs and profits margin of airlines instead of the results from The Initiator is another approach the could offer insight in the profitability of the aircraft.

Appendix A

Patents

Two patents, see figure A-1.



(a) Section added right behind the cockpit

(b) Modular connection device for an airplane body

Figure A-1: Two patents

Appendix B

Flexibility optimization process

The five primary steps of the optimization design method according to Lewis [46] are presented in figure B-1 on page 80.

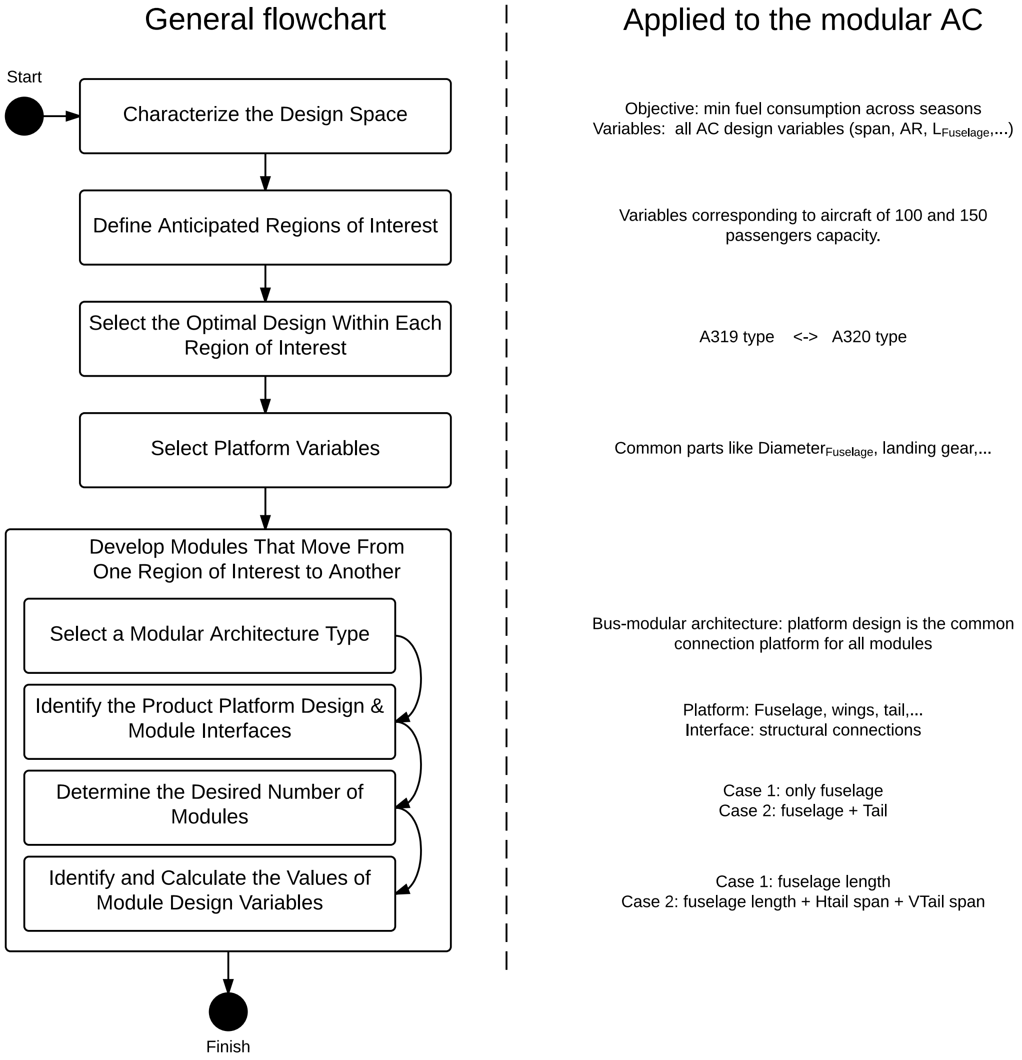


Figure B-1: Flow chart describing the 5-step multiobjective optimization design method.

Appendix C

Initiator Input

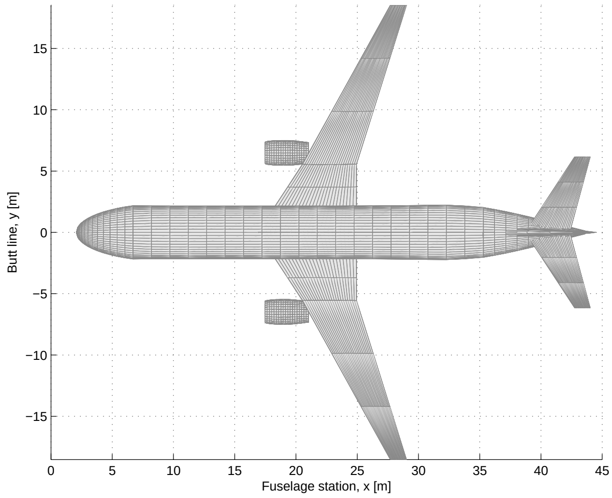
The input for the Initiator of the small and large versions are given hereunder:

Design parameter	Small aircraft	Large aircraft
Pax	100	150
PayloadMass	13600	20400
TakeOffDistance	1721	1960
LandingDistance	1491	1509
Fuselage diameter	4.31	
CruiseMach	0.78	
Altitude	11278	
Range	4800	
NumberOfFlights	100000	
AirworthinessRegulations	FAR-25	
TimeToClimb	4000m in 10min	
LDmax	16	
SFC	0.5	
FFStartUp & FFTaxi	0.99	
CLmaxLanding	2.8	
CLmaxTakeOff	2.2	
CLmaxClean	1.2	
WingAspectRatio	9.5	
WingLocation	Low	
TailType	Standard	
Root, kink, tip Airfoil	SC20614, SC20612, SC20610	
Engine bypass ratio	6.0	

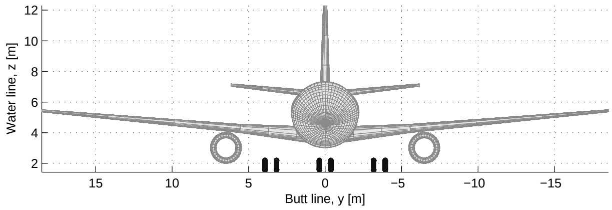
Appendix D

Initiator Output

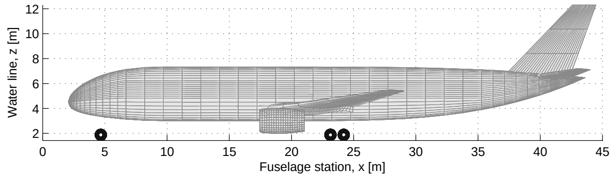
The different figures resulting form the conceptual design of the Initiator are given hereunder.



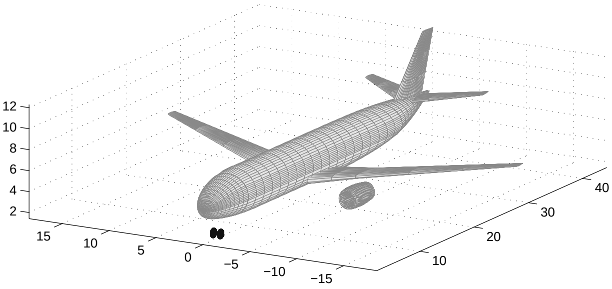
(a) Top View



(b) Front View

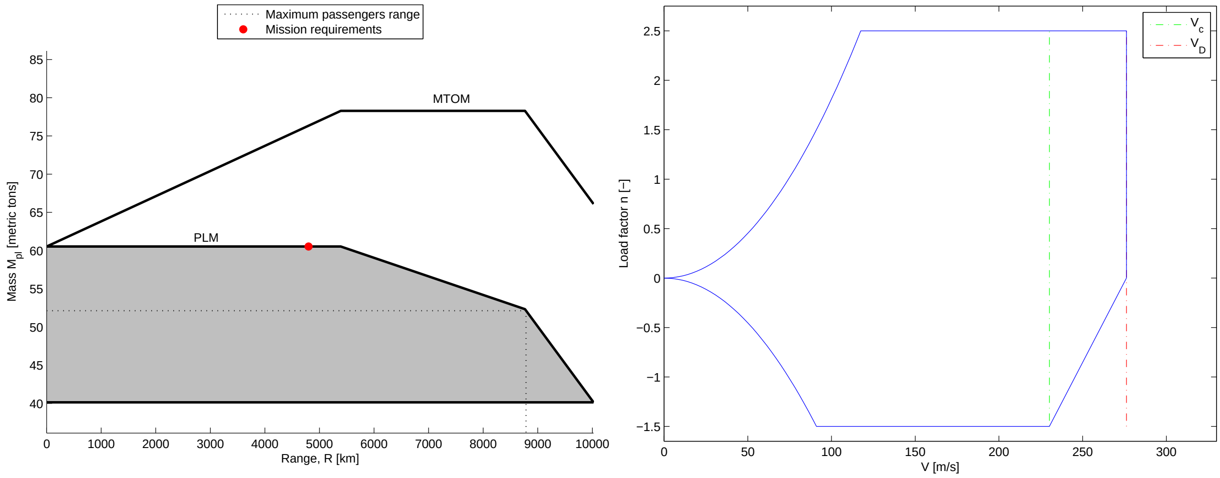


(c) Side View



(d) 3D View

Figure D-1: Typical aircraft geometry (all dimensions in meters)



(a) Payload-Range

(b) V-n diagram

Figure D-2: Typical operational performance diagrams

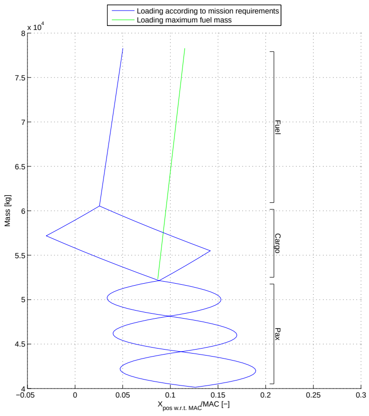
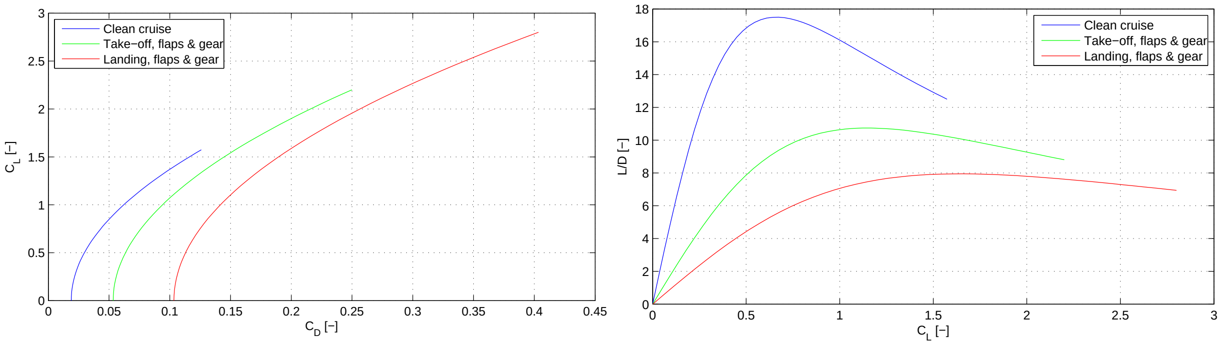


Figure D-3: Typical loading diagram



(a) Drag polar

(b) Aerodynamic efficiency of the aircraft

Figure D-4: Typical aerodynamic results

Appendix E

Modified version of the Initiator

Files of the Initiator requiring modification are identified with a 1:

File			**Wing**	**Tail**	**Engine**
Sizing Modules	@Class1WeightEstimation	MissionEstimation	1	1	1
	@WingThrustLoading	turboFanConstraints	0	0	1
	@GeometryEstimation	run	1	0	0
		estimateWing	1	0	0
		estimateControlSurfaces	0	1	0
Analysis Modules	@Class2WeightEstimation	getMainWingWeight	1	0	0
		getWingWeight	0	1	0
	@Class25WeightEstimation	weightEstimation	1	1	0
	@EMWETWeight	runEMWET	1	0	0

Table E-1: Required modifications

The modified Initiator allows to define aircraft parts. To do so, inputs have to be sent to different modules as can be seen in table E-2. If an input needs to be used to define a particular aircraft part, a 1 is used, else a 0 indicates no influence between the input and the aircraft part.

ModuleInput		**Aircraft parts**			
Module	**Input**	**Fuselage**	**Wing**	**Tail**	**Engine**
Class1WeightEstimation	MTOM1	0	1	0	1
	OEM1	0	1	0	1
WingThrustLoading	InputEngineThrust	0	0	0	1
	RefArea	0	1	0	1
GeometryEstimation	FuselageDiameter	1	0	0	0
	WingSpan	0	1	0	0
	WingRootChord	0	1	0	0
	RefArea	0	1	0	0
	RefMAC	0	1	0	0
	HTailSpan	0	0	1	0
	HTailRootChord	0	0	1	0
	VTailSpan	0	0	1	0
	VTailRootChord	0	0	1	0
Class2WeightEstimation	MainWingWeight	0	1	0	0
	HTailWeight	0	0	1	0
	VTailWeight	0	0	1	0
Class25WeightEstimation	MainWingWeight	0	1	0	0
	HTailWeight	0	0	1	0
	VTailWeight	0	0	1	0
EMWETWeight	MainWingWeight	0	1	0	0

Table E-2: Inputs required per aircraft part

Hereunder is an example of the fuselage, wing, tail and engines being defined according to table E-2:

```xml
<moduleInputs>
        <input module="PlotTool">
                <plotModules>Geometry,DesignConvergence</plotModules>
        </input>
        <input module="Class1WeightEstimation">
                <MTOM1>59980</MTOM1>
                <OEM1>32720</OEM1>
        </input>
        <input module="WingThrustLoading">
                <InputEngineThrust>112975</InputEngineThrust>
                <RefArea>144.40</RefArea>
        </input>
        <input module="GeometryEstimation">
                <FuselageDiameter>4.31</FuselageDiameter>
                <WingSpan>37.04</WingSpan>
                <WingRootChord>8.08</WingRootChord>
                <RefArea>144.40</RefArea>
                <RefMAC>4.74</RefMAC>
                <HTailSpan>12.31</HTailSpan>
                <HTailRootChord>3.65</HTailRootChord>
                <VTailSpan>5.84</VTailSpan>
                <VTailRootChord>5.40</VTailRootChord>
        </input>
        <input module="Class2WeightEstimation">
                <MainWingWeight>7919</MainWingWeight>
                <HTailWeight>747</HTailWeight>
                <VTailWeight>605</VTailWeight>
        </input>
        <input module="Class25WeightEstimation">
                <MainWingWeight>7919</MainWingWeight>
                <HTailWeight>747</HTailWeight>
                <VTailWeight>605</VTailWeight>
        </input>
        <input module="EMWETWeight">
                <MainWingWeight>7919</MainWingWeight>
        </input>
</moduleInputs>
```

Appendix F

Validation of family design tool

F-1 Case 2: maximum number of different aircraft types in fleet

MNT = 1:

```
All RELEVANT solutions are unique.
===>Solution number 1<===
Solution number 1 requires 1 different AC types and costs 0.42464 mEuro/day.
The fleet is composed of:
4 AC of type 1.
0 AC of type 2.
0 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2  3  4
```

MNT = 3:

```
All RELEVANT solutions are unique.
===>Solution number 1<===
Solution number 1 requires 3 different AC types and costs 0.30644 mEuro/day.
The fleet is composed of:
1 AC of type 1.
1 AC of type 2.
2 AC of type 3.
0 AC of type 4.
```

```
Aircraft 1 flies route(s): 1
Aircraft 2 flies route(s): 2
Aircraft 3 flies route(s): 3  4
```

MNT = 4:

```
All RELEVANT solutions are unique.
===>Solution number 1<===
Solution number 1 requires 4 different AC types and costs 0.30541  mEuro/day.
The fleet is composed of:
1 AC of type 1.
1 AC of type 2.
1 AC of type 3.
1 AC of type 4.
Aircraft 1 flies route(s): 1
Aircraft 2 flies route(s): 2
Aircraft 3 flies route(s): 3
Aircraft 4 flies route(s): 4
```

F-2 Case 3: increasing the passenger demand

For increasing the passenger demand on te first route in order to need a third aircraft:

```
All RELEVANT solutions are unique.
===>Solution number 1<===
Solution number 1 requires 2 different AC types and costs 0.44764 mEuro/day.
The fleet is composed of:
3 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

For increasing the passenger demand on te second route and see that the extra passenger is taken car of by the larger capacity of plane 1, so only 4 aircrafts are required in total:

```
All RELEVANT solutions are unique.
===>Solution number 1<===
Solution number 1 requires 2 different AC types and costs 0.30938 mEuro/day.
The fleet is composed of:
```

```
2 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

For increasing the passenger demand on te third route in order to need a third aircraft:

```
===>Solution number 1<===
Solution number 1 requires 2 different AC types and costs 0.35077 mEuro/day.
The fleet is composed of:
2 AC of type 1.
0 AC of type 2.
3 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

For increasing the passenger demand on te second route and see that the extra passenger is taken car of by the larger capacity of plane 3, so only 4 aircrafts are required in total:

```
For increasing the passenger demand on te first route in order to need a second aircr
\begin{verbatim}
All RELEVANT solutions are unique.
===>Solution number 1<===
Solution number 1 requires 2 different AC types and costs 0.30938 mEuro/day.
The fleet is composed of:
2 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

F-3 Case 4: decreasing the passenger capacity

For decreasing the seating capacity of the first aircraft by one:

```
All RELEVANT solutions are unique.
===>Solution number 1<===
```

```
Solution number 1 requires 2 different AC types and costs 0.44661  mEuro/day.
The fleet is composed of:
3 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

For decreasing the seating capacity of the second aircraft by one:

```
All RELEVANT solutions are unique.
===>Solution number 1<===
Solution number 1 requires 2 different AC types and costs 0.30938  mEuro/day.
The fleet is composed of:
2 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

For decreasing the seating capacity of the third aircraft by one:

```
All RELEVANT solutions are unique.
===>Solution number 1<===
Solution number 1 requires 2 different AC types and costs 0.34728  mEuro/day.
The fleet is composed of:
2 AC of type 1.
0 AC of type 2.
3 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

For decreasing the seating capacity of the fourth aircraft by one:

```
===>Solution number 1<===
Solution number 1 requires 2 different AC types and costs 0.32408 mEuro/day.
The fleet is composed of:
2 AC of type 1.
0 AC of type 2.
```

```
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

F-4 Case 5: increasing the distance

For increasing the distance of the first route and aircraft from 7000 to 9000 km:

```
All RELEVANT solutions are unique.
===>Solution number 1<===
Solution number 1 requires 2 different AC types and costs 0.38591 mEuro/day.
WARNING: AC type 1 has insufficient block time to complete the fligth.
The fleet is composed of:
3 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

F-5 Case 6: decreasing the CASK

For decreasing the CASK of the first aircraft to 0:

```
Solution number 1 requires 1 different AC types and costs 0.125 mEuro/day.
The fleet is composed of:
4 AC of type 1.
0 AC of type 2.
0 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2  3  4
```

For decreasing the CASK of the second aircraft to 0:

```
Solution number 1 requires 2 different AC types and costs 0.23202 mEuro/day.
The fleet is composed of:
1 AC of type 1.
3 AC of type 2.
0 AC of type 3.
```

```
0 AC of type 4.
Aircraft 1 flies route(s): 1
Aircraft 2 flies route(s): 2  3  4
```

For decreasing the CASK of the third aircraft to 0:

```
Solution number 1 requires 2 different AC types and costs 0.27722 mEuro/day.
The fleet is composed of:
2 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

For decreasing the CASK of the fourth aircraft to 0:

```
Solution number 1 requires 2 different AC types and costs 0.32408 mEuro/day.
The fleet is composed of:
2 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

F-6 Case 7: decreasing the Cost of Ownership

For decreasing the Cost of Ownership of the first aircraft to 0:

```
Solution number 1 requires 2 different AC types and costs 0.26158 mEuro/day.
The fleet is composed of:
2 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

For decreasing the Cost of Ownership of the second aircraft to 0:

```
Solution number 1 requires 2 different AC types and costs 0.32408 million euros per d
The fleet is composed of:
2 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

For decreasing the Cost of Ownership of the third aircraft to 0:

```
Solution number 1 requires 2 different AC types and costs 0.30658 mEuro/day.
The fleet is composed of:
2 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

For decreasing the Cost of Ownership of the fourth aircraft to 0:

```
Solution number 1 requires 2 different AC types and costs 0.32408 mEuro/day.
The fleet is composed of:
2 AC of type 1.
0 AC of type 2.
2 AC of type 3.
0 AC of type 4.
Aircraft 1 flies route(s): 1  2
Aircraft 3 flies route(s): 3  4
```

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