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Business Jet Conceptual Design: A Cost-Driven Approach

Tesi di Laurea Magistrale in
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Abstract

The continued growth in Business Jets usage indicates that this sector can no longer be treated as a minority market. The objective of this thesis is first to analyse the current BJ market and, in more detail, the European continent. Leading European countries such as France, Germany, and the UK dominate on aspects such as business aircraft utilisation and traffic. There is a strong division within the industry, both in terms of aircraft manufacturers and the solutions proposed to potential customers. Successively, a preliminary sizing methodology is explicitly proposed for business jets, using the Hyperion tool created at the Politecnico di Milano. The software allows precise and reliable data to be obtained thanks to the engine and airframe weight regression modifications. Next, a sensitivity analysis is presented on fundamental parameters linked to different areas, such as aerodynamics, propulsion and structural. The results show how an improvement in these fields brings significant benefits to aircraft performance. Later, the thesis deals with the conceptual design of a MidSize BJ with long-haul characteristics. The result is an aircraft with performance and specifications similar to those found in a MidSize BJ, which can be flown for distances over 6 000 nmi, offering a viable alternative to those currently on the market. After which, the NBJ is evaluated using models for calculating operating costs used in aviation and compared with MidSize and Long-Range aircraft. Finally, through the definition of different scenarios, the NBJ is evaluated and compared with the alternatives present, subsequently showing a detailed analysis of the variation of operating costs according to the different annual use of the aircraft, i.e. whether used for short-, medium- or long-haul routes. The results show that the NBJ represents an innovative and economically advantageous option for those requiring a BJ MidSize but with performance specifications that allow long-haul flights if needed.

Keywords: Business Jets market, Business Jet conceptual design, innovative design, long-range aircraft, operating cost, aircraft utilisation.

Abstract in lingua italiana

La continua crescita sull'utilizzo dei Business Jet indica come questo settore non può più essere trattato come un mercato totalmente a parte. Ne segue che l'obbiettivo di questa tesi è di analizzare in prima battuta il mercato attuale dei BJ a livello mondiale e con maggior dettaglio nel continente europeo. I paesi europei principali quali Francia, Germania e Regno Unito dominano su aspetti quali l'utilizzo e il traffico degli aerei business. Si evince come vi è una forte divisione all'interno dell'industria, sia per quanto concerne i produttori di aeromobili sia per soluzioni proposte ai possibili clienti. Successivamente viene proposta una metodologia di dimensionamento preliminare specifica per i Business Jets, tramite l'utilizzo del tool Hyperion, nato all'interno del Politecnico di Milano. Il software, grazie a delle modifiche sulle regressioni per il peso dei motori e dell'airframe, permette di ottenere dati precisi e affidabili. Di seguito, viene presentata un'analisi di sensitività su alcuni parametri fondamentali, legati a diversi ambiti quali aerodinamico, propulsivo e strutturale. I risultati evidenziano come un miglioramento in questi campi porta notevoli benefici per le performance dell'aereo. IN seguito, la tesi affronta il design concettuale di un BJ di categoria MidSize con caratteristiche da lunga percorrenza. Il risultato finale è un aereo che presenta performance e specifiche simili a quelli presenti in un BJ MidSize, ma che consente di volare per tratte superiori alle 6 000 nmi, proponendo una valida alternativa a quelle presenti attualmente sul mercato. In seguito, l'NBJ viene valutato tramite modelli per il calcolo dei costi operativi usati in ambito aeronautico e confrontato con aerei di categoria MidSize e Long-Range. Infine, tramite la definizione di diversi scenari, l'NBJ viene valutato e confrontato con le alternative presenti, mostrando successivamente una dettagliata analisi sulla variazione dei costi operativi in base al differente utilizzo annuale dell'aeromobile, ossia se usato per tratte a corto, medio o lungo raggio. I risultati evidenziano come l'NBJ rappresenti una opzione innovativa ed economicamente vantaggiosa, per coloro che necessitano di un BJ MidSize ma con specifiche di performance che permettano, se richiesto, di affrontare voli a lunga percorrenza.

Parole chiave: Mercato dei Business Jets, design concettuale di un Business Jet , design innovativo, aereo a lungo-raggio, costi operativi, utilizzo aeromobile.

Contents

Introduction

Motivation

The private and business flight sector has always been seen as an isolated market, where luxury, onboard comfort and rapidity in connecting two or more destinations dominate. Although the costs of acquiring and maintaining a private aircraft are affordable for a few, the market is currently seeing strong growth. In particular, after the Covid-19 pandemic, many passengers have chosen to fly via air taxi/air charter companies, as they are less crowded and entail less risk. According to recent studies proposed by CE Delft and commissioned by Greenpeace Central and Eastern Europe (CEE) [19], the numbers of business flights in Europe in 2022 were 572 806, a remarkable 50 % more than the numbers in 2021. The same is analogous in 2020-2021. From 2019 to 2022, the market grew by 7 %, according to the latest Assessment proposed by EUROCONTROL [28], a clear sign that this sector is becoming increasingly relevant. Concerning the distances flown in 2022, 55 % of flights are below 750 km, but the demand for flights above 3 000 km is also growing strongly.

From the data shown above, it is clear that the aviation industry is experiencing significant growth. In this context, there is a strong interest in achieving ambitious goals such as reducing emissions and being more economically friendly. This should apply to not only commercial aviation but also the business sector, looking to move forward to develop new solutions. There are many possibilities, and numerous studies on identifying new technologies that can be scalable on different categories of aircraft have already been carried out. One example is the SIENA project (Scalability Investigation of Hybrid Electric concepts for Next-generation Aircraft [13]), where the feasibility of using new propulsion systems was investigated, for example, by substituting standard kerosene with hydrogen. This represents a massive challenge for aviation, as many technical issues must be addressed before seeing a zero-emission commercial aircraft in the sky. The goal is to achieve these results by 2050, following several paths. The latest Aviation Outlook proposed by EUROCONTROL [26] illustrates how these objectives can be pursued. These include the development of more efficient conventional aircraft, using electricity and hydrogen for the propulsion system, and in particular, adopting SAF (Sustainable Aviation Fuel), which could lead to a 40 % reduction in emissions by 2050.

Against this backdrop, this thesis seeks to address several issues regarding improving aircraft performance to reduce fuel consumption and associated costs in the context of business aviation. In addition, an attempt is made to propose an innovative solution to offer a viable and efficient alternative in an increasingly fragmented sector.

Literature review

This thesis covers numerous topics related to the business jet industry, from preliminary design and cost evaluation to a current market survey. To correctly analyse each case, several references in the field of aircraft design and many online references are used to provide essential information for the work.

For the first part of the thesis, which focuses on analysing the BJ sector and subsequent analysis of the current market, various online references and public databases are used. To understand the categorisation of BJs according to size and installed propulsion, online site such as [29] is used, thanks to which it is possible to frame the sector better. Concerning market research, data from CIRIUM and EBAA are crucial. Today, CIRIUM [17] is the industry leader in aviation analytics, providing global data and analytics solutions to leaders in finance, aerospace, travel, governments, airlines and more. It currently manages more than 300 terabytes of data, ranging from schedules to routes, aircraft configurations to passenger numbers. Data from CIRIUM provide a better understanding of the worldwide division of the industry, both in terms of fleet and aircraft utilisation. EBAA [5], on the other hand, stands for European Business Aviation Association and is the leading organisation for business aircraft operators in Europe, representing more than 700 companies across the value chain of the European business aviation industry. EBAA provides a wealth of data on business aircraft utilisation in Europe, the busiest routes and the most trafficked airports through the EBAA Yearbook.

The second part of the thesis deals with the preliminary sizing of the Business Jet through the use of the Hyperion tool, developed in the DAER of the Politecnico di Milano. Consequently, the references are limited and lead back to the sites of the BJ manufacturers exploited to obtain information and characteristics of the aircraft used to validate the code [8] [4].

The last part of the thesis deals with the conceptual design of a BJ MidSize Long-Range, then assessed via calculating operating costs in defined scenarios. For the first part of the design, the use of Hyperion together with known references on the subject, such as the design books by J. Roskam [35], D. Raymer [33], M.H. Sadraey [39] and S. Gudmundsson [31] are essential. Concerning the calculation of operating costs, the works of S. Barcellona [15] and A. d'Aniello [18], together with the Unifier-19 project [2], are fundamental to frame the different cost calculation methodologies. Also, in this part, data from EUROCONTROL [27] and SEA [40] are used to refine the calculation of direct costs better. Finally, data from EBAA [5] is still crucial for defining scenarios, thanks to information on routes flown and average flight times for each aircraft.

Structure of the work

The thesis is divided into three main chapters, excluding the introduction and conclusion. Each chapter deals with the following topics:

- **Chapter 1: Business Jet Market Analysis:** this chapter deals with a detailed analysis and description of the business aircraft sector from the point of view of the current fleet, the principal activities carried out and flight performance. First, the classification of BJs according to size and type of installed propulsion is illustrated, detailing the differences. Next, the current European fleet is presented, analysing the different categories of BJs present and the principal OEMs. A look at traffic in Europe is shown immediately afterwards. Lastly, data to describe the aircraft's main operational activities are shown, and finally, the BJs' performance in their respective categories is analysed from a global view.
- **Chapter 2: Business Jet Preliminary Sizing:** the chapter deals with the preliminary sizing of BJs using the Hyperion tool, created by the DAER of the Politecnico di Milano. The procedure is first illustrated, presenting the aircraft for preliminary sizing, along with the specific modifications on historical regressions to obtain the weight of the engines and airframe. The results are validated, comparing them with real aircraft and highlighting the differences. Finally, a sensitivity analysis of various flight parameters is proposed.
- **Chapter 3: Conceptual Design of a MidSize Long-Range Business Jet:** this chapter deals with the conceptual design of a MidSize category business jet with the capability of long-haul flights, called NBJ. The chapter is divided into three macro sections. The first deals with the sizing of the aircraft, describing the initial objectives, initial assumptions and requirements, and finally, showing the results. The second section introduces methods for calculating Aircraft Operating Costs, examining the various terms and highlighting the differences. The results

obtained are then analysed and discussed. The last section introduces multiple scenarios where it is possible to compare the NBJ with its potential competitors and then assume different types of utilisation to identify which is the best from an economic point of view.

1 | Business Jets Market Analysis

Business Jets are one of the most promising and attractive markets in the world of aviation in the coming years. Compared to the world of airliners, it represents a small but rich slice of the market. Today, those not strictly in the industry may think that business jets are used for transporting rich people for leisure, such as going on holiday, but this is different. As the name also implies, this sector is strongly linked to business and the world of work, allowing thousands of people to flight and reach places where, for obvious reasons, it is not possible to get there by typical airliner. Flying with a Business Jet does not only mean luxurious surroundings and comfort on board, but above all it means flexibility. Today, this sector is seeing remarkable growth, despite various objections to their use, due to excessive air pollution and waste of resources. According to the latest Aviation Outlook 2050 proposed by EUROCONTROL [26], the increase in the use of BJs seems to be constant for the coming years, with a 1.1 % per year growth in the low scenario.

Consequently, this chapter examines aspects of the BJs sector, particularly their division into categories based on size and type of propulsion installed. The following presents the current business aircraft market, focusing on the European continent. In detail, the division between the various business aircraft operators is investigated, proposing data on current traffic, and finally, the performance shared by the current fleet are summarised.

1.1. Business Jet fleet by type

The Business Aircraft family includes a considerable number of models, with specifications and performance covering a wide area. In particular, they range from small planes, such as the Embraer Phenom 100E with an MTOW of 4 800 kg, to aircraft, such as the Gulfstream G650 ER with an MTOW of around 47 000 kg, i.e. almost ten times as much. Thus, it is clear that a division into categories based on size and weight is essential.

The division could be more or less extensive, generally going from five categories to eight. The following division of business jets by type is proposed according to [29]:

- Very Light jets

- Light jets
- MidSize jets
- Super MidSize jets
- Large jets
- Long-range jets
- Executive airliner (or bizliner)

As seen in the following paragraphs, each category has its characteristics, where of which are similar across some of them.

Another possible categorisation is based on the installed propulsion; indeed, business aircraft are divided into three classes: piston aircraft, turboprop aircraft and jets. The most widespread category is jets, followed by turboprops.

1.1.1. BJs fleet by size

As stated before, the BJs are divided according to their size. A more in-depth analysis is now presented.

- **Very Light jets**: they have a capacity of four to eight passengers and are approved for single-pilot operations. This category combines turboprop aircraft's cost-effectiveness and efficiency with a light jet's comfort and performance. Very light jets are cheaper to maintain with respect to their light counterparts and even though they cannot offer a long-range performance, they can operate in airports with short runways. In fact, this category is used in the United States to provide air service in the areas ignored by airliners. In general, they do not have a room for cabin attendants and have limited or no lavatory facilities. Regarding the certification, this class belong to FAR-23 (or CS-23) requirements, with a MTOW of 19 000 lb (8 618 kg). The majority have a MTOW from 3 000 to 5 000 kg and the range is about 1 000/1 200 nmi and endurance from 2 to 3 hours, with a cruise speed up to 350/400 kn. Examples of this category are the Embraer EMB-500 Phenom 100 and HondaJet Elite.

Figure 1.1: HondaJet Elite.

- **Light jets**: the capacity is from six to ten passengers, with two pilots and, in general, no flight attendant, but an onboard lavatory is present. They offer enhanced capacity, comfort and performance compared to very light jets and they can operate in private airstrips and short runways. The majority belongs to FAR-23 category but some of them exceed the MTOW, going to FAR-25 certification. The average MTOW is around 6 800 kg (from 6 000 to 9 000 kg), and flight distance is from 1 400 to 2 500 nmi, with a cruise speed of about 400 kn. Examples are Cessna Citation CJ1/CJ2/CJ3 and the Embraer EMB-505 Phenom 300.

Figure 1.2: Cessna Citation CJ4.

- **MidSize jets**: this category typically accommodates 9-10 passengers, with two pilots, a flight attendant, an onboard lavatory and other features, such as Wi-Fi and phone capabilities. They can still operate out of some short runways but with more remarkable performance than the previous two. They usually fall under the requirements of FAR-25, since the average MTOW is 11 000 kg (up to more than 14 000 kg). These aircraft are also suitable for intercontinental flights since the range is up to 2 500 nmi, able to perform until five hours of no-stop travel at an airspeed around 400 kn. Examples are Cessna Citation Excel and Hawaker 800.

Figure 1.3: Hawker 800.

- **Super MidSize jets**: they can accommodate an average of 9 to 14 passengers with all the comfort of the previous category, including an enclosed lavatory and service galley, making long trips more comfortable. It features a wide-body cabin space and high-altitude capability. Since the MTOW is usually around 18 000 kg, the super mid-size jets belong to FAR-25 requirements. The average range is 3 400 nmi with a cruise airspeed of 400/450 kn, leading to flight until seven hours of non-stop travelling. Some aircraft in this category are the Cessna Citation X, the Gulfstream G280 and Embraer Legacy 500.

Figure 1.4: Gulfstream G280.

- **Large jets**: this category offers all the features in the super-midsize jets, plus some other luxurious equipment and up to two flight attendants. They can transport up to 19 passengers and the MTOW could be more than 18 000 kg. The average range is around 4 000 nmi with a cruise speed of 450 kn, with an endurance of up to nine hours, allowing to perform transatlantic travel. An example is the Dassault Falcon 900.

Figure 1.5: Dassault Falcon 900.

- **Long-range jets**: this class allows travel in complete comfort, above all for a long trip. It features several types of equipment like lie-flat beds, a full-service galley, bathrooms and different areas for resting, dining, work and entertainment. These jets can transport up to 19 passengers, with a range of over 6 500 nmi and a cruise speed of 450 kn. The MTOW is around 40 000 kg and can exceed 45 000 kg. This category includes the Gulfstream G650, the Dassault Falcon 7X and the Bombardier Global Express.

Figure 1.6: Bombardier Global Express.

- **Executive airliner (bizliner)**: the category refers to some airliners converted into business jets. Usually, they are used by VIPs, press o to transport sports teams. They are more expensive than other types of business jets and could have some operational restrictions, such as runway length. Of course, they offer more space and capability. The number of passengers and flight attendants could vary depending on the aircraft's use. The range could easily reach 6 000 nmi with a cruise speed of 450 kn. The MTOW is over 70 000 kg and this class belongs to FAR-25 (or CS-25) requirements. In this class, it is possible to find the Airbus Corporate Jet and the Boeing Business Jet, just the standard airliner converted into a business jet. The most spread aircraft are the business variant of the Boeing 737 and Airbus A320 family.

Figure 1.7: ACJ320 (Airbus A320).

1.1.2. BJs fleet by installed propulsion

In addition to the classification by size, it is fair to mention the division by propulsion type. Although most business aircraft use two jet engines, Turboprop aircraft are on the market. North America dominates the global market with more than two-thirds of total aircraft in operation. In Europe, the ratio between private jets and turboprops is around 2:1. In general, the percentage of turboprops is growing, proving the fact that turboprops offer the right compromise in terms of cost and performance. According to [30], turboprops have several advantages over the traditional Business Jet: they can accommodate an average of up to 8 passengers with an approximate endurance of 2 hours.

The principal difference is related to the range: traditional business jets can reach up to 6 500 nmi, whereas turboprops generally have a range up to 1 500 nmi. However, it is interesting to note that, based on an estimation made in the USA (2018), 80 % of the flights were under the two hours threshold, meaning that turboprops could have performed the flight too without any limitations. Of course, the flight time changes, since the cruise speed for turboprops is lower, but the advantages are still numerous. For instance, the cost of a two hours flight could be 40 % less compared to a jet. Moreover, turboprops

could reach difficult spots, able to land on short runways, on grass or gravel.
Finally, the comfort on board is equal if not better than conventional jets, since the operating altitude could be less than 20 000 ft, avoiding the presence of air turbulence that occurs at an altitude from 25 000 to 35 000 ft. Two widespread Business Turboprops on the market are illustrated herein in Figure 1.8.

(a) Pilatus PC-12.

(b) King Air 350.

Figure 1.8

1.2. BJs fleet in Europe

The Business Jets in Europe is a sector that, despite the crisis due to the Covid-19 pandemic, is experiencing an outstanding period of growth and renewal. Overall the fleet is quite heterogeneous, with a predominance of Business Jets over Business Turboprops. According to EBAA Fleet tracker [6], the five used most aircraft are in order:

1. Cessna Citation Excel/XLS
2. King Air 200
3. Pilatus PC-12
4. Embraer Phenom 300
5. Bombardier Global Express

As it is possible to note, two of them are Turboprops, confirming their percentage over the total number of Business Aircraft. Referring to the latest EBAA fleet report [6] (December 2022), there is a based fleet of 3 856 aircraft, which can be subdivided into six categories: single-engine turboprop, twin-engine turboprop, light jets, midsize jets, heavy jets and bizliners. The following Figure 1.9 provides a better understanding of how the aforementioned categories are distributed.

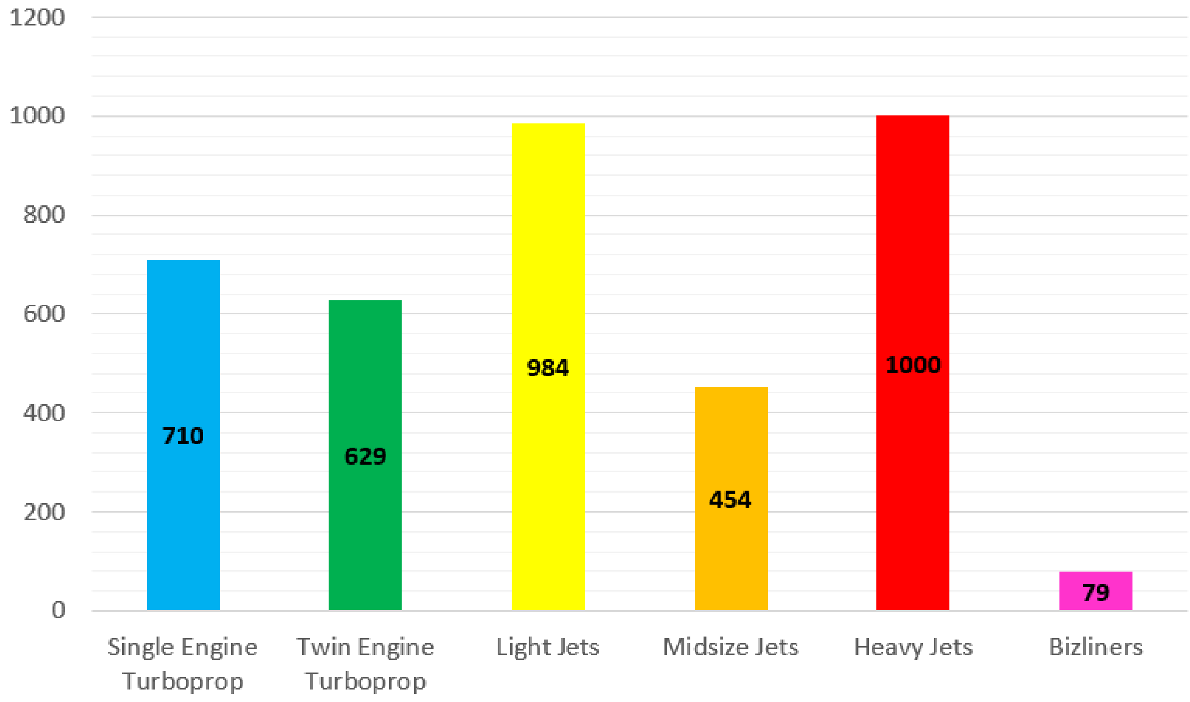


Figure 1.9: Business Aicraft categories distribution [6].

The two most spread categories are Light and Heavy jets, but it is interesting to note that the Turboprops categories occupy a significant role in the sector.

Another worthwhile aspect is the European Fleet from the OEMs point of view. Dividing all the Business aeroplanes into two categories, respectively jets and turboprops, it is visible in Figure 1.10 that there is domination by Textron Aviation. Indeed, this company included not only the famous Cessna but also Beechcraft and Hawker. Apart from Textron, there is a clear-cut between the manufacturers that produce one category or the other.

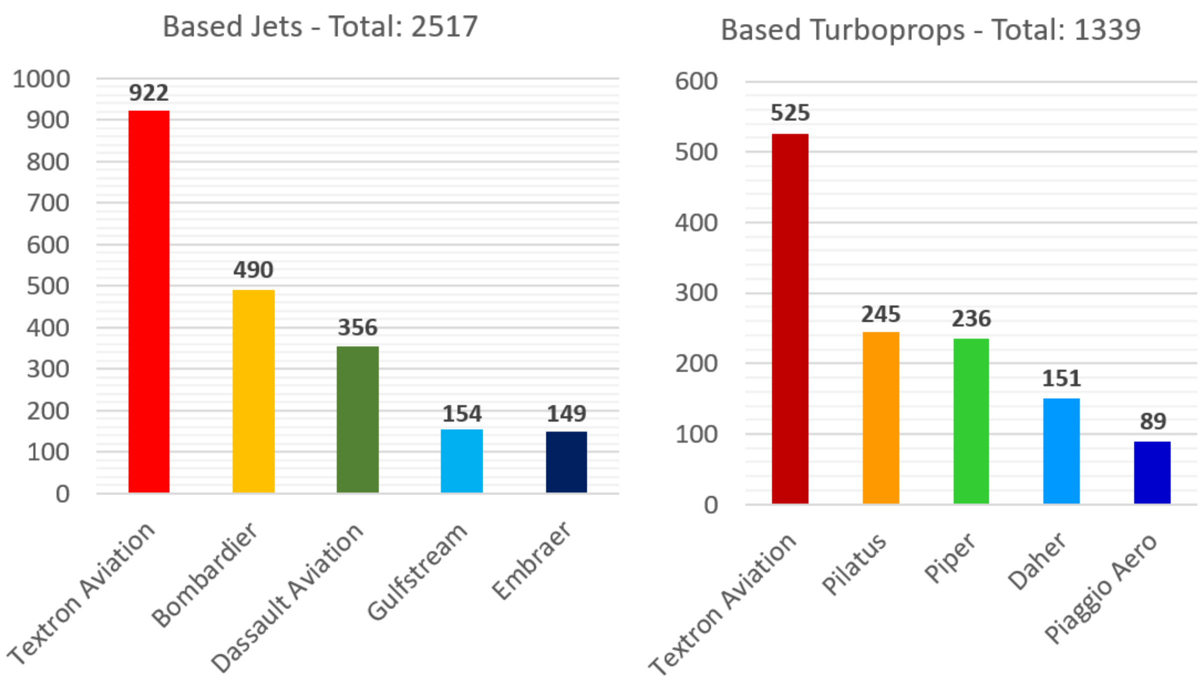


Figure 1.10: OEMs distribution [6].

The last two points for the European fleet are the country distribution of the based fleet and the number of aircraft registered per one hundred inhabitants. As is visible in Figure 1.11, the major of BJs are situated in Germany, followed by France and the United Kingdom. Italy took 5th place with a considerable number of 195 aircraft registered.

Instead, putting the data in proportion to the population, it is evident in Table 1.1 that a few countries, such as Switzerland and Austria, show a considerable number of BJs per one hundred inhabitants; this is simply due to the low population but with a higher number of movements. Indeed, some cities like Geneve, Zurich and Wien are the most trafficked in Europe. Lastly, Malta represents a separate case. First, this country has a significantly low population being a little island; secondly, the tax regime is relatively low, although higher than a few decades ago, but certainly less stringent than in large European countries.

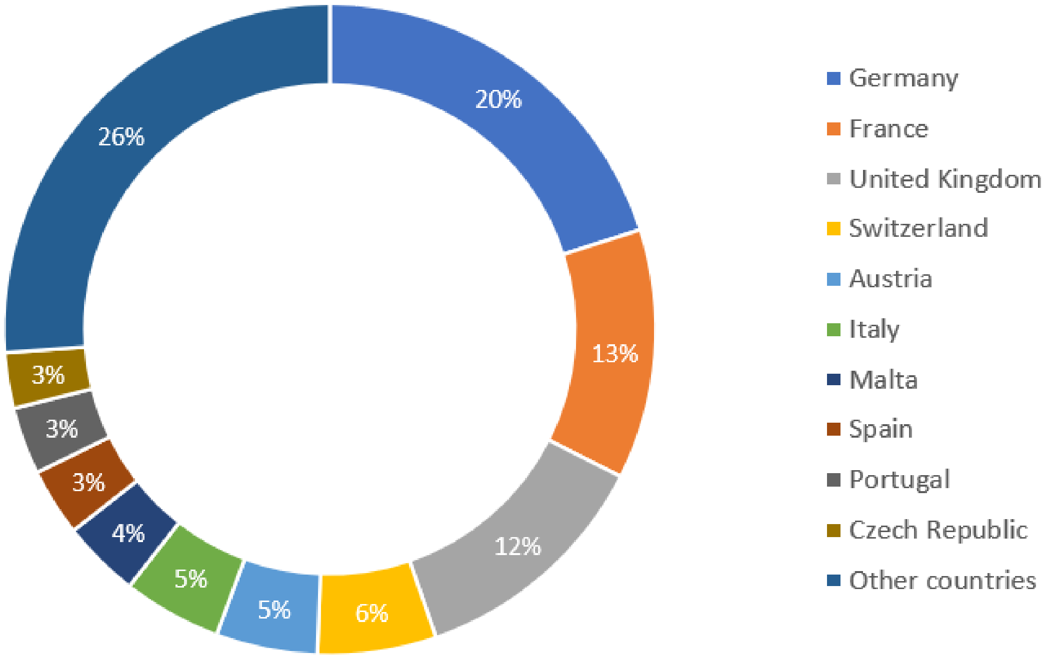


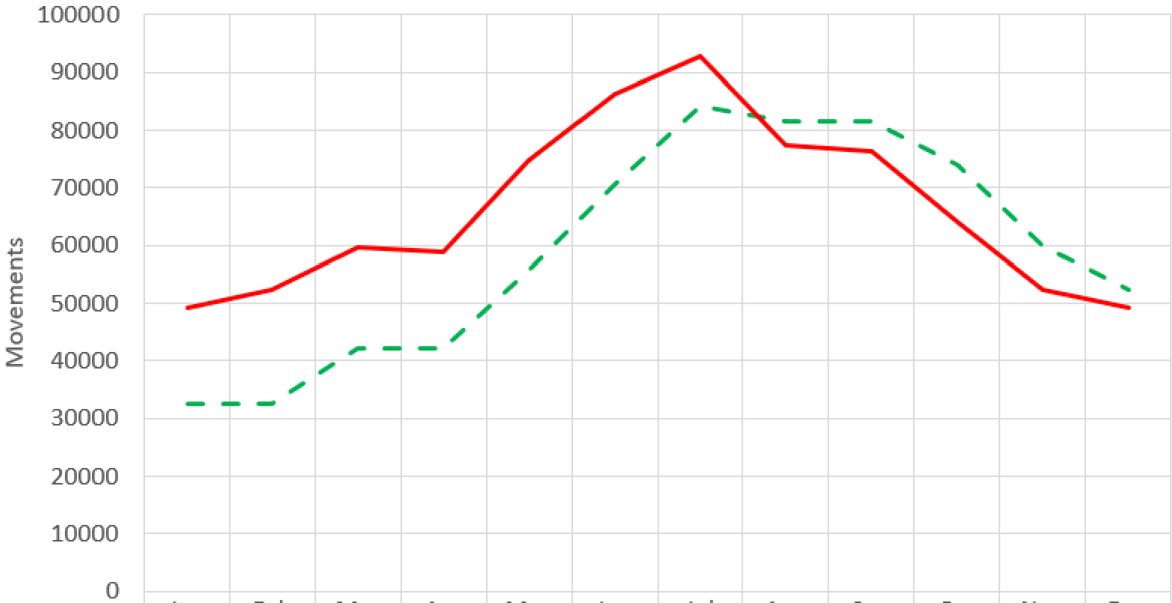
Figure 1.11: Business Aicraft country distribution [6].

Country	Populations	Based Fleet	BJ/100k Inhab.
Germany	8 3200 000	800	0.96
France	6 775 000	495	0.73
UK	6 733 000	489	0.73
Swiss	8 703 000	235	2.70
Austria	8 956 000	201	2.24
Italy	59 110 000	195	0.33
Malta	518 536	154	29.70
Spain	47 420 000	134	0.28
Portugal	10 330 000	133	1.29
Czech Rep.	10 510 000	110	1.05

Table 1.1: Number of BJs per one hundred inhabitants [6].

1.2.1. BJs Europe fleet traffic

Recent events regarding the health and geopolitical situation have definitely affected Business Jet traffic in recent years. As is already known, the Covid-19 pandemic drastically reduced movements in 2020, and although the following year brought remarkable growth, the last year (2022) saw steady growth until the summer months and then showed a marked decline, with lower movement numbers than in 2021. Even though the traffic growth compared to the precedent year is around 11.8 %, according to EBAA Traffic Tracker [7], the Figure 1.12 helps to understand the negative trend in the last months of the year, showing worse performance than in 2021. A plausible explanation may be the recent events in Ukraine, where the invasion by the Russian Federation led to a general ban on flights to and from Russia itself, and subsequently almost entirely cancelled traffic from Ukraine and reduced traffic from some Baltic countries such as Estonia, Latvia and Lithuania.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2021	32559	32460	42078	42172	55742	70639	84144	81631	81499	74009	60008	52456
2022	49332	52314	59611	59001	74709	86152	92911	77298	76242	63965	52435	49182

Figure 1.12: Comparison of BJs movements: 2021 Vs 2022 [7].

Another topic regarding air traffic is the airports most chosen by BJs' travellers. Drawing up a ranking updated to December 2022, at the top of the ranking is Paris Le Bourget airport in France, followed by Geneve Cointrin in Switzerland and Farnborough Civ in the UK. In Italy, Milan Linate is the most trafficked Italian airport, but is in the 8th place, behind other important areas such as Nice or London.

Focusing now on the most travelled routes, the airports mentioned before remain in top positions. Figure 1.13 helps to understand the main Europe routes, along with Table 1.2 listing the five busiest routes. It is clear that France, Switzerland and the United Kingdom are the most frequently visited destinations, mainly for business reasons; other ways are chiefly for leisure/holiday purposes, such as Milano Linate to Olbia Costa Smeralda or Ibiza to Palma de Mallorca.

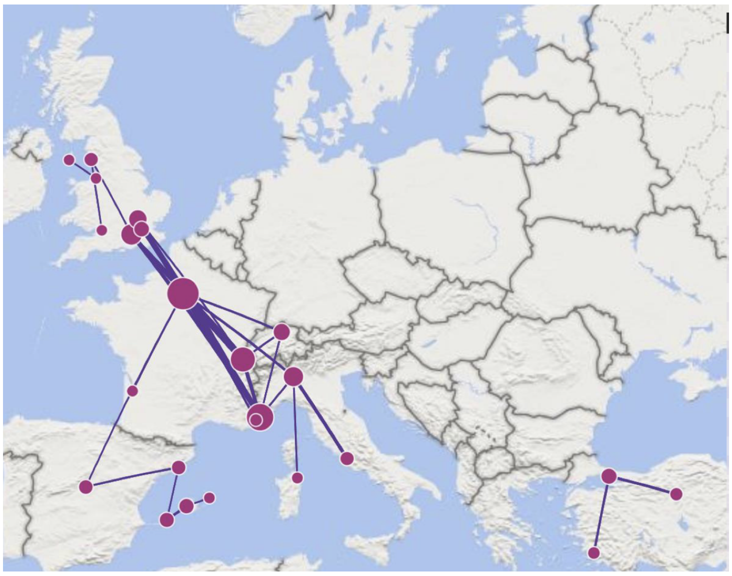
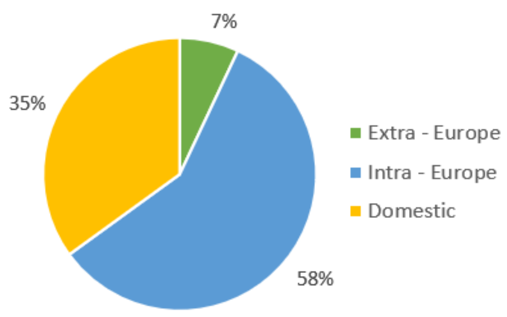


Figure 1.13: Top European routes (updated at Dec 2022 [7]).

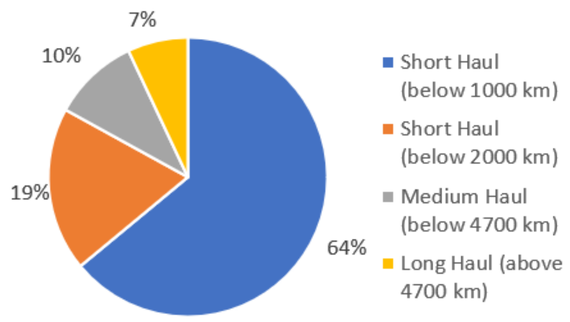
Airport 1	Airport 2	Movements
Paris Le Bourget [FR]	Geneva Int. [CH]	3 632
Paris Le Bourget [FR]	Nice Côte d'Azur [FR]	2 800
Nice Côte d'Azur [FR]	Farnborough [UK]	1 848
Geneva Int. [CH]	Nice Côte d'Azur [FR]	1 783
Roma Ciampino [IT]	Milano Linate [IT]	1 702

Table 1.2: Top European airport routes (updated at Dec 2022 [7]).

A final important aspect is the traffic of BJs from a geographical point of view. As far as destinations are concerned, 58 % of the flights are intra-Europe, while 35 % are domestic and only 7 % are extra-Europe. In addition, the above data mentioned, plus the distinction of flights according to the distance covered in their mission, is shown in Figure 1.14.



(a) BJs activity by destination.



(b) BJs activity by distance travelled.

Figure 1.14: Business Jets Activity [7].

It is clear that more than half of the flights in Europe are short-haul, particularly below 1 000 km. These data are also reinforced by CE Delft's latest study on private aviation emissions in Europe [19]. Indeed, Figure 1.15, shows a histogram containing the distances of all the 2022 flights, and it is evident that most flights are under 750 km. In detail, the highest percentage is in flights between 250 and 500 km, i.e. 24 % of all flights. Finally, an interesting portion of flights above 3 000 km stands out, growing by 6 % since 2020.

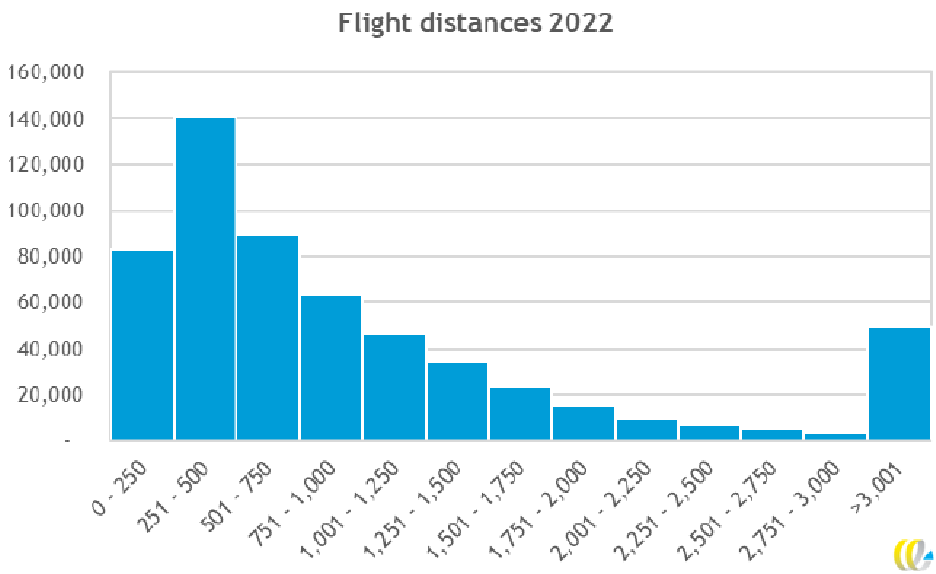


Figure 1.15: Histogram containing the distances of all flights in 2022 [19].

1.3. BJs fleet by activity

Looking in detail at the European market, several private companies are operating as air taxi services, connecting different cities on the old continent and reaching cities that are difficult to reach by scheduled aircraft. Some instances of the major European companies are LunaJets, NetJets and ExecuJet.

Moving towards a global point of view, the North America dominates the business jet market, which holds more than 70 % of all aircraft worldwide. Based on recent estimations [43], currently there are 21 979 business aircraft and only North America has 15 547 of them, whereas Europe occupies second place in the market. The business jets market is growing with a CAGR (Compound Annual Growth Rate) of 4/5 %.

Most aircraft are used for business purposes, particularly from CIRIUM data [17], private company usage and air taxi/air charter, occupying 82 % of the market. The other percentage is occupied by private usage (5 %), utility (5 %) and other (5 %). Business jets are also used for private purposes, for transporting passengers, cargo and for military use. The data just presented are illustrated in Figure 1.16.

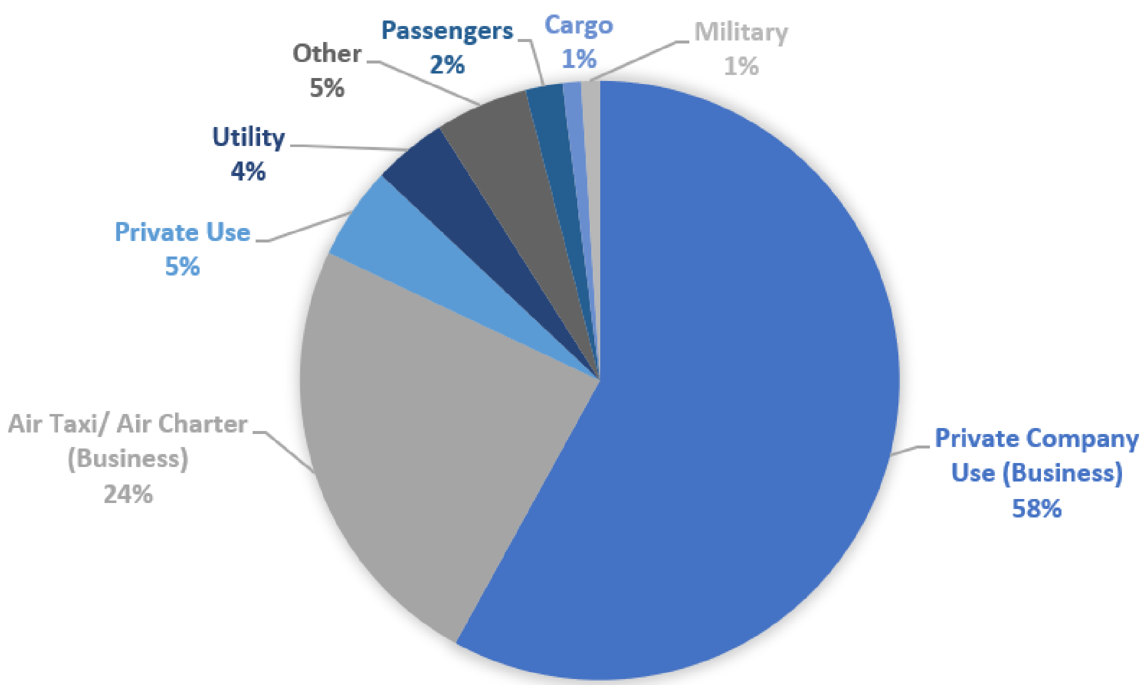


Figure 1.16: BJ fleet by usage in percentage [17].

Another notable data to understand clearly the market is the percentage of the business aircraft category for every usage, dividing all the aircraft into five categories, i.e. Business turboprop, Mid-range, Long-range, Light and Bizliners. Even in this figure, it is notable that, except for the Bizliners, most of the flights are devoted to services such as air taxi/air charter and private company usage, i.e. for business purposes.

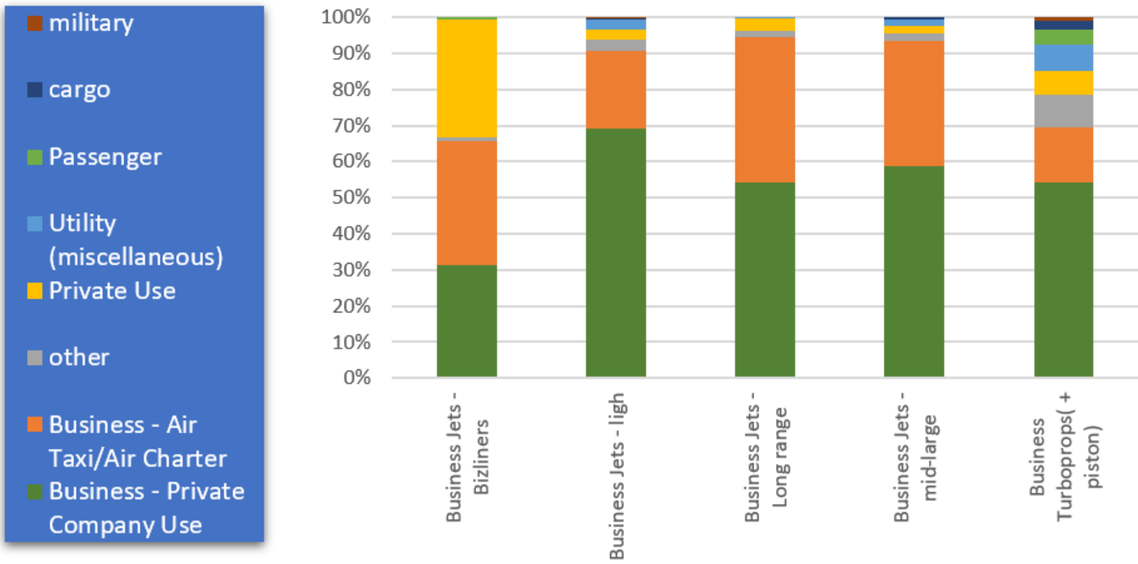
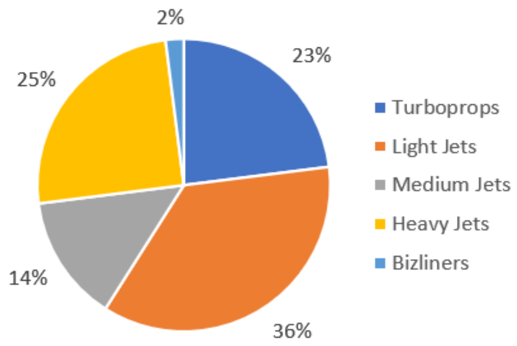


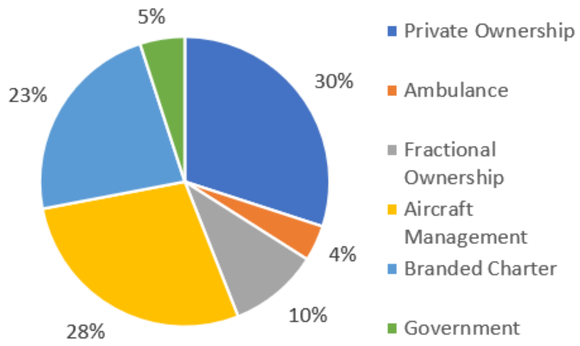
Figure 1.17: Usage of BJs fleet by category [17].

1.3.1. BJs fleet by activity in Europe

Europe ranks second in the world for passenger transport by Business Jet. The distribution of the various categories and their utilisation is analysed using data from EBAA. First, looking at Figure 1.18a, it is possible to note that the majority of the BJs fleet is composed of Light Jets and Turboprops; in detail, they almost count 60 % of the European fleet. Secondly, Figure 1.18b presents the division of the fleet by the operator's activity. As already seen in the previous section, a conspicuous part is dedicated to Air Taxi and private companies (i.e. Aircraft Management and Branded Charter). In addition, the European sector shows a higher percentage of Private Ownership compared to global data (30 % compared to 5 %).



(a) BJs European fleet by category.



(b) BJs European fleet by activity.

Figure 1.18

1.4. Current Fleet Technical Performance

Making a more general overview, the trend of business jets is moving toward increasing performance. Indeed, several manufacturers have upgraded their models, including electronic instruments in the cockpit, such as EFIS, or improving the performance by installing a new version of the motor, leading to lower consumption and emission and modifying the wing design by installing, for instance, winglets.

From a broad point of view, it is possible to note that each category has several common points. For instance, apart from their similar MTOW, the very light and light category mount similar engines, particularly those produced by Williams International, an American manufacturer. These categories generally present two engines, each mounted in a nacelle on the side of the rear fuselage, a T-tail and a low wing, with a supercritical profile in numerous models to reduce the drag.

Moving up a category, the mid-size and super mid-size business jet tends to have two engines mounted on the side of the rear fuselage, with a T-tail or a cruciform tail, to reduce the weight and dimensions of the horizontal stabiliser. The principal engine manufacturers are Prat & Whitney and Honeywell Aerospace, which propose medium turbofans with a ByPass Ratio (BPR) of around 3/4. These two categories present low and swept wings with supercritical profiles and sophisticated winglets to reduce lift-induced drag. In addition to traditional trailing edge flaps, a few super mid-size jets have leading edge flaps such as Krueger flaps (e.g. Gulfstream G200). The trends of the last years are introducing more composite materials in the airframe, reducing weight and enhancing the performance, and having a complete glass cockpit by installing electronic systems such as FADEC, EICAS (engine-indicating and crew-alerting system) and autothrottle, controlled by a Flight Management System.

Regarding the large and long-range jets, these categories have similar characteristics to the previous ones, particularly for the wings, i.e. sweep and low wing with supercritical profile and winglets. Concerning propulsion, most of the jets present two engines mounted on the side part of the rear fuselage, but there are many of them, in particular those built by Dassault Aviation, which have a trijet configuration (e.g. Dassault Falcon 7X and 8X). In these categories are numerous engine manufacturers, i.e. not only Pratt & Whitney and Honeywell, but also Rolls Royce (e.g. BR700 family) and General Electric. Even for these categories, the trend is to use more composite materials for the wing, fuselage, and traditional aluminium alloys. Some models present thrust reverse and an Auxiliary Power Unit (APU). Certainly, all the BJ categories present a pressurised cabin and a tricycle landing gear.

Business Jet average fleet age

The Business Jets fleet age is an intriguing aspect that helps to understand this sector better. Most current aircraft have an average age between 10 and 15 years, whereas Turboprops and piston aircraft reach an age of more than 20 years. As it is visible in Figure 1.19, the youngest fleet is found among the Bizliners (executive airliners) and the Long-Range, while going down the category also increases the average age. Particularly noteworthy is that half of the Turboprops (and piston aircraft) fleet has an average age of over 20 years; the Light Jets category also has a large percentage of the fleet with a high average age. A plausible explanation may be that in recent years, the market has been highly focused on the MidSize and Long-Range categories since they offer more comfort on board, convenience and the ability to travel long distances.

Fleet Age (yrs)	Bizliners [%]	Long - Range [%]	Mid – Size & Large [%]	Light [%]	Turboprops (+ piston) [%]
0 - 5	10.6	27.2	13.9	15.2	13.0
5 - 10	30.3	30.2	13.1	13.2	13.6
10 - 15	26.9	22.1	24.1	20.4	14.8
15 - 20	18.4	10.7	18.4	12.5	10.0
> 20	13.8	9.8	30.6	38.7	48.5
Average fleet age	**11.75**	**9.45**	**16.45**	**18.17**	**21.44**

Figure 1.19: Distribution of BJs fleet age between categories [17].

2 | Business Jet Preliminary Sizing

This chapter aims to propose a methodology for the preliminary sizing of a Business Jet using the Hyperion tool. Two aircraft of different categories are introduced to test and validate the tool for reliable data, combined with targeted modifications within the code specific to BJs. Finally, taking advantage of the results obtained, various sensitivity analyses are conducted on some of the fundamental parameters of an aircraft, whether related to propulsive, aerodynamic or structural fields.

2.1. Preliminary Sizing Methodology

Hyperion (HYbrid PERformance SimulatION) is a methodology developed by DAER that allows obtaining the preliminary sizing of an aircraft, inserting as input several parameters such as payload, range, cruise and climb speed, types of propulsion and number of engines, but also information related to the aerodynamics aspects (i.e. aspect ratio, C_L, C_{D_0}) and propulsion components (i.e. turboprop/ jet, batteries, fuel cell/ICE and electric motor) [32]. These parameters can be either based on those of real aircraft, or an improvement of a specific discipline can be introduced to reflect the difference between the state of art and historical regressions, or to assess the overall effect of a given improvement.

From these numerous inputs, it performs an initial breakdown of design masses (airframe, fuel, payload, engine), then through a simulation of a specific sizing mission, it corrects the initial guess until it reaches a pre-determined tolerance. The various outputs permit not only to validate and to size a traditional aircraft but also to explore potential improvements in fields such as propulsion and aerodynamics. To better understand all the logical links inside the program, a diagram is shown herein in Figure 2.1.

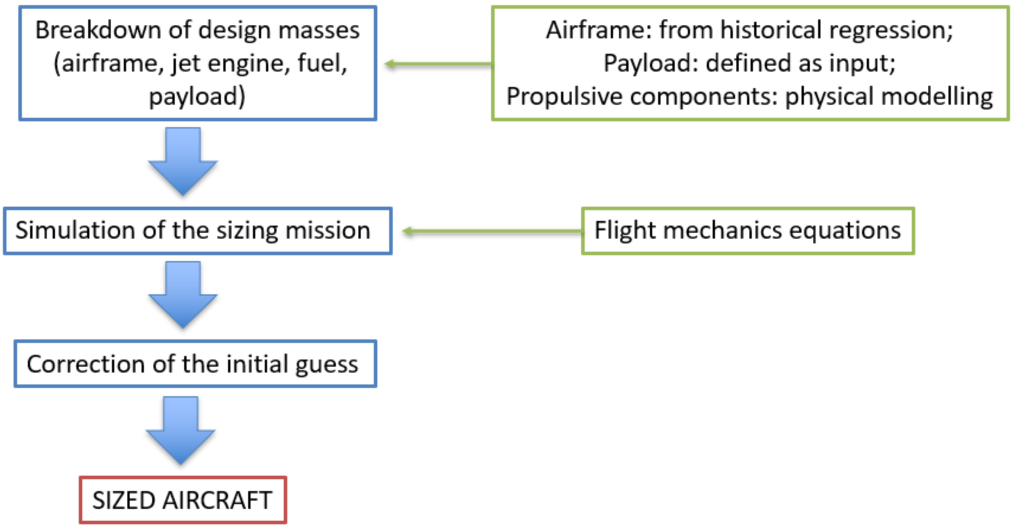


Figure 2.1: Hyperion diagram.

This tool has been tested on several aircraft, in detail, on numerous airliners and innovative aircraft, such as electric and hydrogen ones. Business Jets, have not been tested yet; hence the first objective of this work is to evaluate the performance of Hyperion to obtain a reliable preliminary sizing and validate its results.
Two aircraft are considered for testing and validating Hyperion, a light and a medium size jet, respectively the Embraer Phenom 300E and the Cessna Citation Sovereign +. A visual representation is present herein in Figure 2.2.

(a) Cessna Citation Sovereign +.

(b) Embraer Phenom 300E.

Figure 2.2

The smallest one is a single-pilot-certified light business jet developed by the Brazilian aerospace manufacturer Embraer and it carries up to 11 occupants. The second one

is developed by the American Cessna and is part of the Cessna Citation family. The considered model is the "Plus" version, announced in 2012, and provides new winglets, engines and flight deck.
Before starting with an in-depth view of the aircraft sizing, a few pieces of information regarding the main activities and routes for the two Business Jet selected are shown.

Cessna Citation Sovereign +

The Cessna Citation Sovereign, henceforth called Cessna for brevity, is an American aircraft built by Textron Aviation Inc. that is quite present in the European market. Indeed, according to data collected by EBAA Yearbook [24], the Cessna is the 25th most active business jet in Europe with a fleet of 33 aircraft and 19 918 movements (departures & arrivals). The average flight distance is around 882 km with an average flight duration of 1h 23m. Being an aeroplane out of production since 2021, the fleet's average age is approximately 12 years. Looking now at the traffic aspect, 74.1 % of flight is commercial, followed by 13.1 % of medical/special flight and 12.7 % of non-commercial flight, with Europe as the predominant destination (63.1 %) and the second position occupied by domestic flight (flights within the country of departure). To conclude, the main routes travelled in 2021 are domestic flights in the following countries: Norway, Germany and Italy, with the five main city pairs listed and presented on a map in Figure 2.3 and Figure 2.4.

Figure 2.3: Main Cessna routes in Europe (source: [24]).

CESSNA CITATION SOVEREIGN Top 10 airport pairs – Flights 2021 (both ways)		Flights
Dusseldorf	Friedrichshafen Bodensee	290
Stavanger	Oslo Gardermoen	166
Oslo Gardermoen	Bergen Flesland	130
Trondheim Vaernes AB	Oslo Gardermoen	125
Bergen Flesland	Stavanger	82

Figure 2.4: Main Cessna routes with number of flights (source: [24]).

Embraer Phenom 300E

The Embraer Phenom 300E, hereafter referred to for simplicity as Embraer, is a light aircraft built by the Brazilian aerospace manufacturer Embraer. Again based on data provided by EBAA Yearbook [24], it occupied the 4th place for activity in Europe, with a fleet of 96 aeroplanes and 65 420 movements. Compared to Cessna, being a smaller BJ, the average flight distance is 765 km, whereas the average flight duration is around 1h 17min. The Embraer is in production since 2009, which translates into an average age of 7 years.

Referring now to air traffic, even for the Embraer the majority of the flights are commercial (82.6 %) followed by 16.5 % for non-commercial flights. In this case, as it is a light jet, the percentage of domestic flights is slightly higher than for the Cessna, while obviously, the extra-Europe flights are null. Lastly, the three main routes updated to 2021 are domestic German and French flights, followed by the route between France and Switzerland. A graphical representation of the main routes on a map is shown in Figure 2.5 and the five main routes with the number of flights are listed in 2.6.

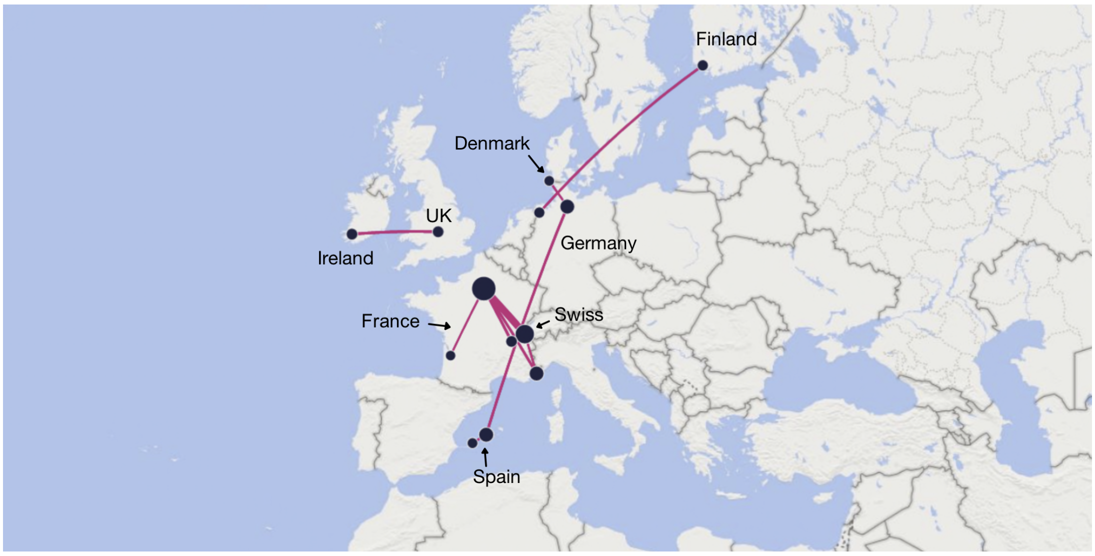


Figure 2.5: Main Embraer routes in Europe (source: [24]).

EMBRAER PHENOM 300 Top 10 airport pairs – Flights 2021 (both ways)

		Flights
Geneva International	Paris Le Bourget	286
Kerry	Stratford-on-Avon	126
Paris Le Bourget	Lyon Bron	124
Palma de Mallorca	Hamburg	120
Paris Le Bourget	Nice Côte d Azur	119

Figure 2.6: Main Embraer routes with number of flights (source: [24]).

2.2. Ad-Hoc Historical Regressions

The tool Hyperion uses several ad-hoc regressions to obtain estimations on some aircraft specifications, such as aerodynamic drag coefficients, engine mass or aircraft airframe mass. With the purpose of achieving reliable results, a few historical regressions have been modified, particularly the ones related to the engine and airframe weights, to make them business jet specific.

2.2.1. Engine weight regression

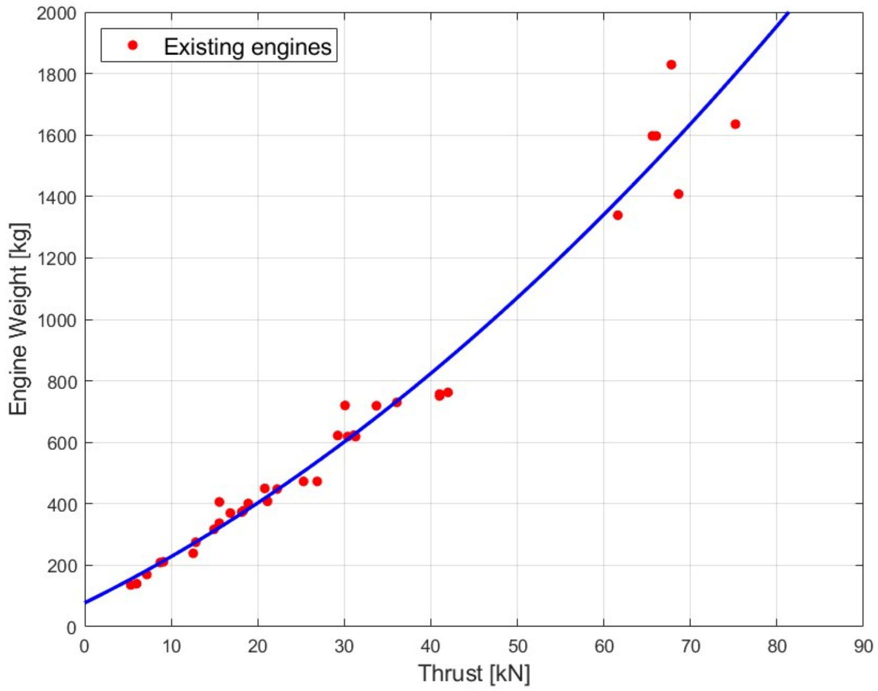
This section deals with developing a specific regression for the weight of engines, as Hyperion generally uses estimates based on airliner-mounted engines, which are, therefore larger.
Collecting the most common engines adopted in the BJ field is fundamental to building a reliable historical mass regression for this application. All the samples used are presented in Table A.1 in Appendix A, gathering a wide variety of engines, from the smallest mounted on the light jets to the heaviest used in the large and long-range jets. To better understand, some of the used samples are shown below in Table 2.1.

Model	Mass [kg]	BPR	Thrust [kN]
Williams FJ44-1AP	209	2.6	8.7
PW545C	377	3.8	18.3
TFE731-5BR	408	3.5	21.1
PW306C	473	4.5	25.3
CF34-3A1	751	6.3	41.0
BR710C4-11	1 597	4.2	65.6

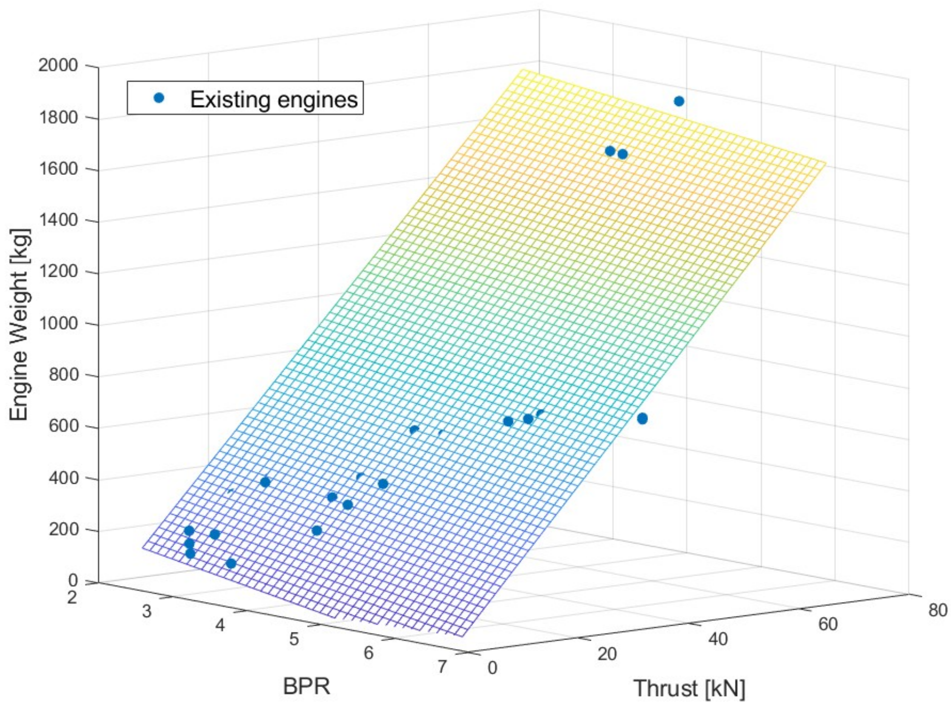
Table 2.1: Engine data used for regression.

The BPR parameter remains in the range from 3 to 6, where it is possible to find a low value for the engines mounted on light aircraft and in the oldest engines. Naturally, the recent trend is to increase the BPR to reduce fuel consumption and improve performance, causing larger engine inlets.

The correlation between the weight and the BPR is crucial to determine which typology of mathematical regression fits better. In detail, four different regressions are considered: linear regression, quadratic regression, multiple linear regression and multiple quadratic regression. The first two do not consider the BPR, only the thrust required, whereas the last two use both the thrust required and the BPR. The quadratic regression and multiple linear regression are shown in Figure 2.7. The choice to represent only these two is pretty straightforward: the linear regression is too simplifying, whereas the multiple quadratic regression is similar to the multiple linear ones. For the sake of clarity, these two last regressions are shown in Figure A.1 in Appendix A.



(a) Quadratic regression.



(b) Multiple linear regression.

Figure 2.7: Ad-hoc historical regressions results.

Since there is no strict correlation between the BPR and the engine weight, for all the tests done to validate Hyperion for the Business Jets, better results are obtained with simple quadratic regression, as it is able to estimate the weight with more accuracy. The mathematical formulation of the quadratic regression is presented herein, with the regression coefficients present in Table 2.3.

$$M_{eng} = p_1 \cdot T_{max}^2 + p_2 \cdot T_{max} + p_3 \tag{2.1}$$

p_1	p_2	p_3
0.1199	13.8660	77.7199

Table 2.2: Engine mass regression coefficients.

2.2.2. Aiframe weight regression

The necessity to modify the airframe weight regression comes from the difficulty of Hyperion in sizing the smallest Business Jets, as the already implemented historical regression was created for the airliner. In this specific case, the effort is contained. The regression is shown in Equation 2.2, using Raymer [33] as reference, with the coefficients in Table 2.3. Only one coefficient, particularly K_{af}, has been tuned to obtain a better correct airframe weight.

$$M_{empty} = K_{af} \cdot (A \cdot M_{TO}^C) \tag{2.2}$$

A/C Model	K_{af}
Sovereign +	1.040
Phenom 300E	1.125

Table 2.3: Empty mass regression coefficient.

2.3. Validation

To size both the Cessna Citation Sovereign + and the Embraer Phenom 300E correctly using Hyperion, all the performance, aerodynamics and propulsion information must be collected in an input file called "AirData" file. In detail, the data are obtained using official brochures for the range, take-off and landing distance and other aspects, whereas EASA technical data are used to derive the engine information, for instance the dimensions, the dry weight and the ITT (InterTurbine Temperature) [23][21]. Lastly, to get information regarding the climb speed, the rate of climb, the cruise speed and its corresponding altitude, FlightRadar24 is used [9].

Once all the data are stored in an AirData file, the sizing through Hyperion can start. Before showing the results obtained, it is crucial to distinguish two different cases; if the wing surface and the airframe mass are constrained, the result is called "Retrofit" (RF), while if there are no constrain of the wing surface and airframe mass, the result is called "Clean Sheet" (CS). This distinction is because when Retrofit sizing is used, the code does not take advantage of the airframe mass regression simply because the airframe mass is already imposed, whereas with Clean Sheet sizing the regression mentioned before assumes a significant relevance.

Lastly, before mentioning the sizing obtained, it is crucial to clarify at which condition of payload and fuel the results are achieved. For the Cessna, the situation with full fuel and a number of occupants of 7 is considered, both for Retrofit and Clean Sheet sizing, whereas for the Embraer an initial condition with 6 occupants, including the single pilot, for the Retrofit sizing is examined, and a situation with full passengers, i.e. 11, and full fuel respecting the MTOW for the Clean Sheet ones. The decision to adopt different payload conditions for the Embraer lies in the fact that Hyperion failed to correctly estimate the aircraft via Clean Sheet sizing by imposing the payload conditions used in Retrofit.

The results are shown below, where it is possible to compare the Retrofit and Clean Sheet sizing for the Cessna with the real aircraft data in Table 2.4 and Table 2.5, while the respective results for the Embraer are presented in Table 2.6 and Table 2.7. The results focus on showing the breakdown of masses and the dimension of the wing surface, including the wing span. A few flight parameters of the sizing mission for the Cessna and Embraer are shown in Figure A.3 and Figure A.4, in Appendix A.

	Real A/C	RF A/C	Error [%]
MTOW [kg]	13 959	14 026	+ 0.5
Empty [kg]	8 083	8 098	+ 0.2
Airframe [kg]	7 034	7 034	+ 0.0
PL + CW [kg]	710	710	+ 0.0
Engines [kg]	1 049	1 064	+ 1.4
Fuel [kg]	5 166	5 218	+ 1.0

Table 2.4: Retrofit result for Cessna Citation Sovereign +.

	Real A/C	CS A/C	Error [%]
MTOW [kg]	13 959	13 534	- 3.1
Empty [kg]	8 083	7 856	- 2.8
Airframe [kg]	7 034	6 832	- 2.9
PL + CW [kg]	710	710	+ 0.0
Engines [kg]	1 049	1 024	- 2.4
Fuel [kg]	5 166	4 967	- 3.8
S [m^2]	50.4	53.2	+ 5.6
b [m]	22.04	22.64	+ 2.7

Table 2.5: Clean Sheet result for Cessna Citation Sovereign +.

	Real A/C	RF A/C	Error [%]
MTOW [kg]	8 415	8 388	- 0.3
Empty [kg]	5 358	5 375	+ 0.3
Airframe [kg]	4 724	4 724	+ 0.0
PL + CW [kg]	629	629	+ 0.0
Engines [kg]	634	651	+ 2.7
Fuel [kg]	2 428	2 384	- 1.8

Table 2.6: Retrofit result for Embraer Phenom 300E.

	Real A/C	CS A/C	Error [%]
MTOW [kg]	8 415	8 581	+ 1.9
Empty [kg]	5 358	5 455	+ 1.8
Airframe [kg]	4 724	4 790	+ 1.4
PL + CW [kg]	1 296	1 296	+ 0.0
Engines [kg]	634	665	+ 4.8
Fuel [kg]	1 761	1 830	+ 3.9
S [m^2]	28.5	42.7	+ 49.8
b [m]	15.91	19.47	+ 22.4

Table 2.7: Clean Sheet for Embraer Phenom 300E.

Based on the results achieved, a few comments must be drawn up; as far as the results obtained in Retrofit are concerned, Hyperion succeeds in getting precise results, correctly dimensioning the aircraft with very high accuracy.

The Clean Sheet sizing needs separate discussions. In this case, the previous regressions in Section 2.2 come into force, particularly concerning airframe mass estimation. The data obtained for the Cessna is excellent, with minimal relative errors in terms of mass and dimensions, while the Embraer deserves a separate discussion. Here, Hyperion correctly estimates the mass breakdown but significantly oversizes the wing area.
A plausible explanation is that the software tends to obtain less reliable data with small aircraft, while it performs better with aircraft close in size to regional/airliners. In addition, the stringent requirements imposed for stall speed and landing distance tend to increase the wing area value, obtained via the aircraft's Sizing Matrix Plot, a cardinal result of preliminary sizing. A more accurate estimate of stall speed and more complete data on landing distance could significantly improve the results.

2.4. Sensitivity Analysis

As is well known, the aviation world is undergoing profound change. It is expected that aircraft will have low, if not zero, emissions in the coming decades. Of course, this path requires time, resources, and ideas to be applied in the field, but there are now numerous studies on possible concrete solutions. These proposals will not only have positive impacts on environmental sustainability but will also bring with them economic benefits. Even in the field of business aircraft, a radical change is needed in the years to come, finding solutions that can be more environmentally and economically friendly.

Consequently, one of the key aspects of this thesis is to evaluate and explore how new aeronautical technologies, such as structure, aerodynamics and propulsion, may benefit the business jets industry and the related market. Hence, the first appealing step that can be done is a sensitivity analysis of certain parameters, such as:

- Zero lift drag coefficient (C_{D_0})
- ByPass ratio
- Range
- Cruise speed
- Airframe mass

These parameters are examined as they allow technological innovation in various aviation disciplines to be considered, permitting an assessment of how they impact the preliminary sizing process of an aircraft. This sensitivity analysis is applied to aircraft obtained by preliminary sizing in Section 2.3.

2.4.1. Sensitivity Analysis on C_{D_0}

A major aspect that significantly influences the MTOW and, in general, the aircraft performance is the drag coefficient at zero lift. Indeed, an increase in drag coefficient at zero lift leads to an increase in the thrust required, i.e. in the fuel consumption and consequent rise in engine mass, leading to an overall increase in all aircraft masses.
It is considered a reduction until 1 % of C_{D_0} to perform a realistic and reliable sensitivity analysis. The tests for both aircraft are executed using a Clean Sheet procedure, starting from a base value of the coefficient obtained with the initial sizing. The obtained results compared with the preliminary sizing are below in Table 2.8 for the Cessna and in Table 2.9 for the Embraer.

	CS A/C	CS A/C - w/mod	Δ [%]
MTOW [kg]	13 534	13 042	- 3.6
Empty [kg]	7 856	7 586	- 3.4
Airframe [kg]	6 832	6 601	- 3.4
PL + CW [kg]	710	710	+ 0.0
Engines [kg]	1 024	986	- 3.7
Fuel [kg]	4 967	4 745	- 4.5
S [m^2]	53.2	51.3	- 3.7
C_{D_0} [-]	0.0189	0.0187	- 1.1
T_{max} [kN]	46.1	44.4	- 3.8

Table 2.8: C_{D_0} sensitivity analysis for the Cessna.

	CS A/C	CS A/C - w/mod	Δ [%]
MTOW [kg]	8 574	8 456	- 1.4
Empty [kg]	5 454	5 380	- 1.4
Airframe [kg]	4 791	4 726	- 1.4
PL + CW [kg]	1 296	1 296	+ 0.0
Engines [kg]	663	654	- 1.4
Fuel [kg]	1 824	1 780	- 2.4
S [m^2]	42.8	42.2	- 1.4
C_{D_0} [-]	0.0167	0.0165	- 1.2
T_{max} [kN]	28.9	28.5	- 1.6

Table 2.9: C_{D_0} sensitivity analysis for the Embraer.

It is easily noticeable that a reduction of the C_{D_0} leads to a general reduction of the MTOW since there is a drop in aircraft friction. This translates into an improved flight performance, thanks for example to a more aerodynamically efficient wing (e.g. using innovative winglets), leading to an aircraft that can perform the same mission but consumes less fuel.

2.4.2. Sensitivity Analysis on the BPR

The engine ByPass ratio has assumed significant importance in the last decades since its increase could lead to a performance benefit, saving fuel and reducing emissions. Therefore, a sensitivity analysis regarding this important parameter is conducted. All the technical information about the engines mounted on the two aircraft tested are from the EASA data sheet and the official brochure from the manufacturer's website. The engine characteristics for both aircraft are presented in Table 2.10.

Model	Dry Weight [kg]	Length [mm]	Diameter [mm]	BPR
PW306D	524.4	1 923	1 139	4.5
PW535E1	317.0	1 679	1 082	4.1

Table 2.10: Aircraft engine specifications.

Both aircraft mount engines built by Pratt & Whitney Canada. The PW300 family is a series of small turbofans developed specifically for the business jet application. The PW500 family is a class of medium-thrust turbofans mounted on numerous Cessna aircraft.

The starting point and the increment tested are herein listed for the Cessna in Table 2.11 and in Table 2.12 for the Embraer, along with the result obtained using a different BPR. The selected increment for BPR refers to engines already on the BJs market (listed in Table A.1); however, these increments remain significantly lower than those on airliner engines.

BPR 5 (+ 0.5)	CS A/C	CS A/C - w/mod	Δ [%]
MTOW [kg]	13 534	12 946	- 4.2
$\mathbf{C_{D_0}}$ **[-]**	0.0189	0.0193	+ 2.1
$\mathbf{T_{max}}$ **[kN]**	46.1	44.2	- 4.2
BPR 5.5 (+ 1.0)	**CS A/C**	**CS A/C - w/mod**	**Δ [%]**
MTOW [kg]	13 534	12 159	- 10.2
$\mathbf{C_{D_0}}$ **[-]**	0.0189	0.0197	+ 4.2
$\mathbf{T_{max}}$ **[kN]**	46.1	41.6	- 9.8

Table 2.11: ByPass Ratio sensitivity analysis for the Cessna.

BPR 4.5 (+ 0.4)	CS A/C	CS A/C - w/mod	Δ [%]
MTOW [kg]	8 574	8 376	- 2.3
C_{D_0} [-]	0.0167	0.0169	+ 1.2
T_{max} [kN]	28.9	28.3	- 2.2
BPR 5 (+ 0.9)	**CS A/C**	**CS A/C - w/mod**	**Δ [%]**
MTOW [kg]	8 574	8 162	- 4.8
C_{D_0} [-]	0.0167	0.0170	+ 1.8
T_{max} [kN]	28.9	27.6	- 4.6

Table 2.12: ByPass Ratio sensitivity analysis for the Embraer.

As shown in the results, an increase in the BPR leads to a general decrease in the MTOW for both aircraft, including the engine weight. This last result concerning the engine's weight may seem misleading although the outcome is correct. Indeed, an increase in the BPR tends to size a more efficient aircraft capable of performing the same mission (i.e. range) but using less fuel, leading to an overall decrease in aircraft weight. The only parameter that follows an opposite direction is the drag coefficient at zero lift which increases since a higher BPR leads to bulkier engines.

2.4.3. Sensitivity Analysis on the Range

The aircraft range is a paramount parameter to consider during an aircraft design. In particular, the Business Jets are divided according to their mileage range. The two aircraft considered for the sensitivity analysis are a light and a medium size jet, offering distinctly different performances. An initial basic range analysis is conducted, simply increasing the range of both aircraft up to 10 %. The results are presented in Table 2.13 for the Cessna and in Table 2.14 for the Embraer. In this case, the time in minutes to complete the mission is also shown.

	CS A/C	CS A/C - w/mod	Δ [%]
MTOW [kg]	13 534	15 947	+ 17.8
S [m^2]	53.2	62.8	+ 18.1
C_{D_0} [-]	0.0189	0.0177	- 6.3
T_{max} [kN]	46.1	54.1	- 17.3
Time [min]	444	487	+ 8.5

Table 2.13: Range (+ 10 %) sensitivity analysis for the Cessna.

	CS A/C	CS A/C - w/mod	Δ [%]
MTOW [kg]	8 574	9 193	+ 7.2
S [m^2]	42.8	45.9	+ 7.3
C_{D_0} [-]	0.0167	0.0162	- 3.0
T_{max} [kN]	28.9	30.9	+ 7.0
Time [min]	248	271	+ 9.3

Table 2.14: Range (+ 10 %) sensitivity analysis for the Embraer.

As expected, an increase without modifying any other parameter, leads to a general rise in the aircraft weight, whereas the C_{D_0} tends to decrease.

It is now interesting to discover how increasing the BPR could increase the range trying to maintain the same MTOW. Hence, further analysis is conducted by setting a new BPR, i.e. increasing and tuning the range to obtain the same aircraft weight. In this way, it is more straightforward to see how the BPR significantly impacts performance. Indeed, using an engine with a higher BPR leads to a more efficient aeroplane, consuming less fuel and consequently being able to increase its range. The results are shown in Table 2.15 and Table 2.16.

BPR 5 (+ 0.5)	Real A/C	RF A/C - w/mod	Δ [%]
MTOW [kg]	13 959	13 959	+ 0.00
Time [min]	N.A.	454	N.A.
R [km]	5 844	6 005	+ 2.7
BPR 5.5 (+ 1.0)	**Real A/C**	**RF A/C - w/mod**	**Δ [%]**
MTOW [kg]	13 959	13 960	+ 0.01
Time [min]	N.A.	469	N.A.
R [km]	5 844	6 196	+ 5.7
BPR 6 (+ 1.5)	**Real A/C**	**RF A/C - w/mod**	**Δ [%]**
MTOW [kg]	13 959	13 961	+ 0.01
Time [min]	N.A.	483	N.A.
R [km]	5 844	6 382	+ 8.4

Table 2.15: Range analysis for the Cessna.

BPR 4.5 (+ 0.4)	Real A/C	RF A/C - w/mod	Δ [%]
MTOW [kg]	8 415	8 416	+ 0.01
Time [min]	N.A.	320.6	N.A.
R [km]	3 908	4 075	+ 4.1
BPR 5 (+ 0.9)	**Real A/C**	**RF A/C - w/mod**	**Δ [%]**
MTOW [kg]	8 415	8 414	- 0.01
Time [min]	N.A.	331.2	N.A.
R [km]	3 908	4 229	+ 7.6
BPR 5.5 (+ 1.4)	**Real A/C**	**RF A/C - w/mod**	**Δ [%]**
MTOW [kg]	8 415	8 415	+ 0.00
Time [min]	N.A.	342.3	N.A.
R [km]	3 908	4 374	+ 10.6

Table 2.16: Range analysis for the Embraer.

Therefore, an increase in BPR can bring significant benefits, such as a rise in the nominal range of up to 500 km. Of course, increasing this parameter brings disadvantages, and one is the larger engine inlet sizes. Indeed, as seen in the last paragraph, a higher BPR leads to a more bulky engine, which could significantly impact the aircraft design. For instance, a more voluminous motor may influence the aircraft's centre of mass or the fuselage dimension since commonly both engines are mounted on the side of the rear part of the fuselage.

To correctly analyse the problem and obtain reliable results, brief research on the actual engines used in the Business Aviation sector is conducted to get data such as the weight, the length, the external diameter, BPR and the nominal thrust at take-off condition. Hence, in Table 2.17 it is possible to see the most common engines used in this sector and their main characteristics.

Model	Year	Dry Weight [kg]	Length [mm]	Diameter [mm]	BPR	Thrust [kN]
PW307A	2007	551	2 185	1 170	4.3	28.49
HTF7500E	2013	618.7	2 280	1 120	4.2	31.30
PW308C	2000	623.5	2 184	1 299	4.1	31.15
CF34-3	1995	757.5	2 616	1 245	6.2	38.83
PW812D	2022	1 237	2 874	1 109	5.5	61.61
GE Passport	2018	1 632.9	3 302	1 380	5.6	78.93
Pearl 15	2018	1 828.8	4 809	1 230	4.8	67.28

Table 2.17: Most spread BJs engines specifications.

As it is possible to note, the general trend is a value of BPR between 4 and approximately 5.5. The only exception in this table is the General Electric CF34-3, an engine mounted on the Bombardier Challenger 650, offering a high BPR with reduced size and weight.

The subsequent step is to estimate the engine dimension, i.e. the fan diameter, through an analytic process. The starting point is the calculation of the Required Thrust and Specific Thrust using Hyperion, by setting in the AirData file the value of the BPR for which the diameter value is desired. Once these data are collected, it is possible to get the mass flow rate by making the ratio between the Required Thrust and Specific Thrust, as shown in Equation 2.3.

$$\dot{m} = \frac{T}{T_{spc}} \tag{2.3}$$

Successively, using a simple equation for the mass flow rate, it is possible to achieve the

Fan Area and so the Fan Diameter, as shown in Equation 2.4.

$$A = \frac{\dot{m}}{\rho \cdot V_{crs}} \tag{2.4}$$

Finally, the results obtained are presented in Table 2.18.

Phenom 300E

BPR	Diameter [m]
4.1	0.94
4.5	0.97
5.0	1.00
5.5	1.03

Sovereign +

BPR	Diameter [m]
4.5	1.22
5.0	1.25
5.5	1.28
6.0	1.31

Table 2.18: Engine diameter analysis.

As it is possible to note, an increase in the ByPass Ratio leads to a rise in the Fan diameter. From these results, it can be seen that the increase in size is not so pronounced. Obviously, considering an increase in BPR is a choice that brings with it numerous other considerations apart from the increased volume; one must examine, for example, whether it does not excessively alter the aircraft's centre of mass or whether, if the engines are mounted on the rear tail, it is not necessary to increase the tail size and/or weight.

2.4.4. Sensitivity Analysis on the Cruise Speed

The cruise speed, along with the range, is one of the more significant parameters when deciding between several aircraft models. Moreover, the customer requests an aeroplane that can offer an extended range with a high cruise speed. However, in this sensitivity analysis, the opposite trend is studied since a slight reduction in the cruise speed leads to a reduction in the fuel burn and the operative cost. For both aircraft, a decrease of 5 % and 10 % in the operational cruise speed is considered, i.e. not varying the maximum operating speed at which the engines are dimensioned. The results are presented in Table 2.19 for the Cessna and Table 2.20 for the Embraer.

V_{crs} - 5 %	CS A/C	CS A/C - w/mod	Δ [%]
MTOW [kg]	13 534	13 060	- 3.5
C_{D_0} [-]	0.0189	0.0193	+ 2.1
T_{max} [kN]	46.1	44.4	- 3.7
Time [min]	444	467	+ 5.2
V_{crs} - 10 %	**CS A/C**	**CS A/C - w/mod**	**Δ [%]**
MTOW [kg]	13 534	12 532	- 7.4
C_{D_0} [-]	0.0189	0.0195	+ 3.2
T_{max} [kN]	46.1	43.2	- 6.5
Time [min]	444	489	+ 9.0

Table 2.19: Cruise speed sensitivity analysis for the Cessna.

V_{crs} - 5 %	CS A/C	CS A/C - w/mod	Δ [%]
MTOW [kg]	8 574	8 428	- 1.7
C_{D_0} [-]	0.0167	0.0169	+ 1.2
T_{max} [kN]	28.9	28.6	- 1.0
Time [min]	248	259	+ 4.6
V_{crs} - 10 %	**CS A/C**	**CS A/C - w/mod**	**Δ [%]**
MTOW [kg]	8 574	8 284	- 3.4
C_{D_0} [-]	0.0167	0.0173	+ 3.6
T_{max} [kN]	28.9	28.0	- 3.1
Time [min]	248	271	+ 9.2

Table 2.20: Cruise speed sensitivity analysis for the Cessna.

As expected, a reduction in the cruise speed results in lower fuel consumption to perform the same mission, so the total aircraft weight is lower since Hyperion executes the sizing relying on the mission imposed in the Airdata file. Again, the only parameter that follows the opposite direction in the C_{D_0}, which shows a slight increase.

2.4.5. Sensitivity Analysis on the Airframe Mass

The last sensitivity analysis conducted is regarding the airframe mass. In the last decades, technological progress has enabled increasingly strong yet lightweight materials to be adopted in the aeronautical field, reducing weight and costs while increasing performance.

Hence, an analysis in this field is conducted. In this case, the investigation is done using a sort of middle way between Retrofit and Clean Sheet sizing; Indeed, the airframe mass is imposed with the modification and the wing surface is unconstrained. A 2.5, 5 and 7.5 % reduction in the airframe mass is considered. This could be translated into adopting more composite material instead of the standard aluminium alloys. The results are shown in Table 2.21 and Table 2.22 below, comparing them with the real aircraft data.

AM - 2.5 %	**Real A/C**	**A/C Mod**	**Δ [%]**
MTOW [kg]	13 959	13 572	- 2.8
S [m^2]	50.4	53.4	+ 5.9
T_{max} [kN]	52.6	50.3	- 4.4
AM - 5 %	**Real A/C**	**A/C Mod**	**Δ [%]**
MTOW [kg]	13 959	13 308	- 4.7
S [m^2]	50.4	52.3	+ 3.7
T_{max} [kN]	52.6	49.4	- 6.0
AM - 7.5 %	**Real A/C**	**A/C Mod**	**Δ [%]**
MTOW [kg]	13 959	13 041	- 6.6
S [m^2]	50.4	52.3	+ 3.7
T_{max} [kN]	52.6	49.5	- 5.9

Table 2.21: Airframe mass sensitivity analysis for the Cessna.

AM - 2.5 %	**Real A/C**	**A/C Mod**	**Δ [%]**
MTOW [kg]	8 415	8 241	- 2.1
S [m^2]	28.5	41.0	+ 44.0
T_{max} [kN]	30.9	30.5	- 1.3
AM - 5 %	**Real A/C**	**A/C Mod**	**Δ [%]**
MTOW [kg]	8 415	8 079	- 4.0
S [m^2]	28.5	40.2	+ 41.0
T_{max} [kN]	30.9	29.9	- 3.2
AM - 7.5 %	**Real A/C**	**A/C Mod**	**Δ [%]**
MTOW [kg]	8 415	7 917	- 5.9
S [m^2]	28.5	39.4	+ 38.2
T_{max} [kN]	30.9	29.3	- 5.2

Table 2.22: Airframe mass sensitivity analysis for the Embraer.

A more pronounced reduction in the airframe mass is not considered, since there is no certainty that the sized aircraft is capable of transporting the same number of passengers as such a significant reduction of the airframe mass would necessarily cause a reduction of its size as well.

3 | Conceptual Design of a MidSize Long-Range Business Jet

The Business Jet branch has various differences from the typical airliner sector. As previously mentioned in Chapter 1, Business Jets are divided according to their dimensions and, apart from private owners, a conspicuous share is devoted to Air Taxi and Air Charter services, i.e. by private business companies. All these companies should possess an appropriate fleet to satisfy the majority of customers. Generally, most flights are short- and medium-range, as they are less complex, highly demanded, and significantly profitable. Naturally, the long-range class is not overlooked; rather, it offers an essential service linking different continents quickly, efficiently and comfortably.

The latter requirement leads companies operating mainly in the short- and medium-haul sector to equip themselves with one or more long-haul aircraft, even though these aircraft may be used sparingly or at all for very long routes. This problem can lead to economic repercussions for the company. Thus trying to overcome this possible problem, the idea is to offer the market a MidSize Business Jet with the capability, if requested, to fly long-range routes with lower ownership and operating costs than a standard long-range business jet. The proposed name for the aircraft is NBJ (i.e. New Business Jet). This chapter, therefore, deals with presenting a possible solution, designing a suitable one and comparing it with direct competitors on the market.

3.1. Aircraft configuration and preliminary sizing

This section aims to describe the preliminary design and sizing process for a medium-sized business aircraft that has the capability to fly long distances. First, the objective of the sizing is defined, then the possible configuration is described and finally, the results are compared with an existing business jet such as the Dassault Falcon 2000.

3.1.1. Goal of the design

The objective, as already mentioned in the introduction to this chapter, is to size a medium business jet that can offer performance beyond its category. An existing Midsize Business Jet is the starting point to achieve a consistent solution. The aircraft under consideration is the Dassault Falcon 2000, a jet produced by French Dassault Aviation, introduced in 1995 as an evolution of its predecessor Falcon 900. Thus far, according to [14], more than 600 units have been sold and several improvements have been introduced over the years, making it one of the most widespread and efficient aircraft on the European continent. Figure 3.1 illustrates the last aircraft version, the Dassault Falcon 2000 LSX.

Figure 3.1: Dassault Falcon 2000LSX (source:[3]).

The first step in designing the NBJ is to understand and quantify in more detail how improvements in propulsion, aerodynamics and structures can positively impact key points such as weight, fuel consumption and flight performance. Therefore, the individual improvements are first analysed and later merged, presenting all solutions.

The aircraft to which these upgrades are applied is the one from a Clean Sheet sizing of the Dassault Falcon 2000, henceforth called for brevity MRBJ (Medium Range Business Aircraft). The results are obtained considering a nominal range of 4 000 nmi, excluding the diversion, plus a payload of 6 passengers and 2 crew members. Each passenger weighs 85 kg plus 50 kg of baggage, whereas each crew member weighs 85 kg.
The principal characteristics of the MRBJ, along with the ones of the Falcon 2000, are shown herein in Table 3.1. Flight parameters for the MRBJ sizing mission are shown in Figure A.5 in Appendix A.

	Falcon 2000	MRBJ	Error [%]
MTOW [kg]	19 414	19 671	+ 1.3
Empty [kg]	10 824	11 023	+ 1.8
Airframe [kg]	9 577	9 830	+ 2.7
PL + CW [kg]	980	980	+ 0.0
Engines [kg]	1 247	1 192	- 4.4
Fuel [kg]	7 610	7 668	+ 0.8
S [m^2]	49.0	65.6	+ 33.9
b [m]	21.4	24.7	+ 15.4
T_{max} [kN]	62.3	59.5	- 4.5

Table 3.1: Comparison between Dassault Falcon 2000 LSX and MRBJ.

MRBJ-E: Engine improvements

The propulsion sector is undoubtedly the one that is most under discussion and where most efforts are being concentrated, not only because governmental or European institutions have set themselves challenging targets such as zero emissions by a specific date, but because even a small improvement today can lead to cost savings, both in terms of lower fuel consumption and lower handling costs, for example by reducing carbon dioxide emission-related taxes.

Consequently, this section examines the engine used on board the Falcon 2000 (and on the MRBJ) and applies improvements to build a new one, such as: increasing the BPR, increasing the EPR and increasing the diameter of the engine itself. The engine mounted on the Falcon 2000 is the PW308C, a turbofan jet engine developed by Pratt & Withney Canada specifically for business jet applications. The resulting aircraft with the engine improvements is called MRBJ-E (E stands for Engine).

Intending to get a consistent solution, these engine upgrades are not entirely arbitrary; indeed, the main engine characteristics for the MRBJ-E are similar or even slightly better to an existing modern engine mounted on the Bombardier Challenger 650 (a midsize BJ), the General Electric CF34-3B. This engine with its variants is used in numerous business and regional aircraft, showing excellent performance. To get a better understanding, the engine specification of MRBJ-E, alongside the CF34-3B and PW308C are shown in Table 3.2, according to the EASA data sheets ([22] and [20]).

Model	Length [m]	Diameter [m]	BPR	EPR
MRBJ-E Engine	N.A.	1.30	6.5	23.25
PW308C	2.18	1.29	4.5	15.00
CF34-3B	2.62	1.26	6.2	21.00

Table 3.2: Engine's specification comparison.

As it is possible to note, there is a considerable distinction between the PW308C and the MRBJ-E engine, whereas these differences are less pronounced with the CF34-3B. In detail, the BPR is slightly increased, considering a possible development in the immediate future, as there is a small difference; the engine diameter rises as it is directly connected to the BPR. Lastly, the EPR is also increased, assuming there is an improvement in the materials used in the hot part of the engine in the years to come, i.e. an increase in the TIT, leading to global growth in the engine's efficiency. Ultimately, it is notable in Table 3.2 that there is no engine length for the MRBJ-E; this is because Hyperion does not take as inputs the engine length to estimate its weight and performance nor it does compute the engine length as an output.

Once all these data have been defined, it is possible to insert them into the MRBJ Airdata file, replacing the original ones, and starting with a new full aircraft sizing using Hyperion, obtaining the so-called MRBJ-E aircraft. The results are herein shown in Table 3.3, comparing the MRBJ and its improved version MRBJ-E.

	MRBJ	MRBJ-E	Δ [%]
MTOW [kg]	19 671	16 282	- 16.2
Empty [kg]	11 023	9 850	- 9.0
Airframe [kg]	9 830	8 866	- 7.4
PL + CW [kg]	980	980	+ 0.0
Engines [kg]	1 192	984	- 21.1
Fuel [kg]	7 668	5 452	- 28.4
S [m^2]	65.6	53.8	- 18.0
b [m]	24.7	22.4	- 9.3
C_{D_0} [-]	0.0199	0.0216	+ 8.5
T_{max} [kN]	59.5	49.3	- 17.1

Table 3.3: Comparison between MRBJ and MRBJ-E.

From the table above, it is immediately visible that there is a global reduction of the masses, particularly regarding the fuel necessary for the mission and the engines. Some changes are easy to guess, such as the decrease in fuel because the engine is more efficient or the increase in C_{D_0} because the engine is bulkier. Instead, the reduction in the engine's weight could be misinterpreted. The explanation is reasonably straightforward: Hyperion estimates the engine's weight based on the thrust required to make the flight; as the aircraft's weight, in this case, is lower due to lower fuel consumption, the thrust required also is more downward. This results in a lighter engine.

MRBJ-A: Aerodynamics improvements

Undoubtedly, the aerodynamic field plays a vital role in the design and improving flight performance. Several steps have been taken in recent decades, such as using sophisticated winglets or in-depth studies of airfoils. As far as winglets are concerned, several manufacturers of business jets have updated their models to include wingtip devices, leading to a decrease in fuel consumption and a slight increase in performance, such as range and flight endurance. With regard to the aerodynamic improvements that are taken into account, a slight improvement in the lift coefficient C_L in the terminal phases of flight and a decrease in the induced drag coefficient C_{D_i} through an increase in Oswald's factor e, are considered to simplify the procedure. The aircraft with these improvements is called MRBJ-A (A stands for Aerodynamic). Parameters such as maximum lift coefficient at take-off and landing ($C_{L_{TOmax}}$, $C_{L_{LNDmax}}$) and e are inputs in the aircraft AirData file, and the increment is 0.1 for both.

The results from a Clean Sheet sizing and the inputs are compared with the ones obtained with the MRBJ, as shown in Table 3.5 and Table 3.4.

	MRBJ	**MRBJ-A**	**Δ [%]**
$\mathbf{C_{L_{TOmax}}}$	1.98	2.08	+ 5.0
$\mathbf{C_{L_{LNDmax}}}$	2.3	2.4	+ 4.3
$\mathbf{C_{D_0}}$	0.0199	0.0212	+ 6.5
K	0.0417	0.0379	- 9.1
L/D	17.3	17.6	+ 1.7

Table 3.4: Comparison of aerodynamic parameters between MRBJ and MRBJ-A.

	MRBJ	MRBJ-A	Δ [%]
MTOW [kg]	19 671	18 970	- 4.4
Empty [kg]	11 023	10 579	- 3.9
Airframe [kg]	9 830	9 496	- 3.4
PL + CW [kg]	980	980	+ 0.0
Engines [kg]	1 192	1 083	- 9.1
Fuel [kg]	7 668	7 411	- 5.6
S [m^2]	65.6	60.6	- 7.6
b [m]	24.7	23.7	- 4.0
T_{max} [kN]	59.5	54.2	- 8.9

Table 3.5: Comparison between MRBJ and MRBJ-E.

As in the case of the propulsive improvement, there is still a decrease in aircraft masses, not as marked as before. Clearly, there is a reduction in fuel consumption thanks to a general drag reduction. In detail, it is possible to observe a reduction in the coefficient K, hence a reduction in induced drag, whereas the C_{D_0} slightly increases. On the whole, however, there is an increase in the lift-to-drag ratio.

MRBJ-EA - Engine, aerodynamic and airframe improvements

This last section illustrates the aircraft to which propulsion and aerodynamic modifications have been made. In addition, an improvement in the materials used for the aircraft airframe is considered, assuming a higher use of composite materials and lightening the structure by 10 %. The results are illustrated in Table 3.6.

	MRBJ	MRBJ-EA	Δ [%]
MTOW [kg]	19 671	15 821	- 20.3
Empty [kg]	11 023	9 538	- 13.4
Airframe [kg]	9 830	8 631	- 12.2
PL + CW [kg]	980	980	+ 0.0
Engines [kg]	1 192	907	- 24.0
Fuel [kg]	7 668	5 304	- 32.5
S [m^2]	65.6	50.2	- 23.5
b [m]	24.7	21.6	- 12.5
C_{D_0} [-]	0.0199	0.0229	+ 15.0
K [-]	0.0417	0.0379	- 9.1
L/D [-]	17.3	17.6	+ 1.7
T_{max} [kN]	59.5	45.3	- 23.8

Table 3.6: Comparison between MRBJ and MRBJ-EA.

In the latter case, an improvement can always be noticed in terms of the aircraft's MTOW and aerodynamic lift-to-drag ratio. This version, i.e MRBJ-EA, with the mentioned improvements, is the starting point for the sizing of the MidSize BJ with long-range capability, also known as NBJ.

3.1.2. Cabin layout and configuration

Cabin layout is crucial when a customer has to purchase a new aircraft. In fact, it is common for the aircraft manufacturer to offer its customer the product with a cabin configuration that is as customised as possible and reflects the requirements. In particular, the business jets sector sees a great deal of influence from the customer in the choice of configuration; there are also a large number of accessories, which make the flight experience more comfortable and luxurious. Naturally, this section does not touch on secondary aspects concerning cabin interiors, but only deals with the number of seats and their arrangement, always respecting the available cabin length.

There are three different seats taken into consideration: standard seats, comfort seats and sofas. Moreover, the presented cabin layouts are equal to or similar to the ones used for the Dassault Falcon 2000, thus respecting the cabin length, which is imposed to obtain the MRBJ. These three options permit to create unique cabin configurations, allowing to carry a different number of passengers depending on the selection. In this case, the comfort seat differs from the standard seat only for its larger dimension and the possibility of being rotated to offer greater comfort, whereas the sofa can accommodate up to a maximum of three passengers.

Before presenting the possible options for the cabin layout, it is necessary to deal with an issue, that is the number of beds. Indeed, the latter is crucial when considering long-haul travel; for example, a popular route such as London to New York takes about 8 hours and these flights are often operated at night, allowing passengers to sleep comfortably. Clearly, the number of seats cannot be equal to the number of beds; generally, two seats can compose one bed by supporting a single mattress. The Figure 3.2 helps to visualise the situation better.

Figure 3.2: Bed positioning onboard (source: [12]).

Five possible cabin layouts are listed herein, combining the standard seat, comfort seat and sofa (up to three passengers).

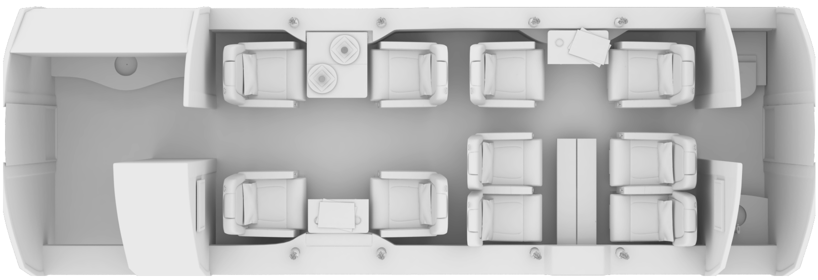
- *Configuration 1:* 6 standard seats + 4 comfort seats;
- *Configuration 2:* 4 standard seats + 4 comfort seats + 1 sofa;
- *Configuration 3:* 4 comfort seats + 2 sofas;
- *Configuration 4:* 8 comfort seats;
- *Configuration 5:* 6 comfort seats + 1 sofa.

Hence, the total number of seats and the corresponding number of beds is shown in Table 3.7 below, then choosing the most flexible and adaptable to different needs.

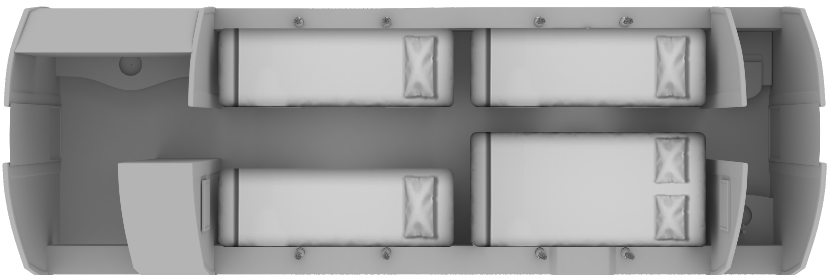
Configuration	Seats number	Beds number
1	10	5
2	11	5
3	10	4
4	8	4
5	9	4

Table 3.7: Cabin layout comparison.

The decision falls on configuration number 1, which is reasonably traditional, flexible, and allows ten passengers to be carried comfortably. The graphical representation of the cabin layout chosen is present in Figure 3.3.



(a) Standard cabin configuration.



(b) Night cabin configuration.

Figure 3.3

3.1.3. Requirements and initial guess

Sizing a Business Jet with long-range capability is not an arbitrary process, hence an initial guess to start and obtain reliable results is fundamental. The starting point is the MRBJ-EA, previously shown in Section 3.1.1. The next step is to impose, by using the aircraft AirData file, a range greater than the nominal one of the MRBJ-EA (equal to the range of the Dassault Falcon 2000), which is 4 000 nmi. The objective is to find a nominal

range that permits flying with the maximum payload and, in the case of boarding less payload, i.e. passengers, allows flying distances greater than 6 000 nmi, a value that can be considered as a constraint for categorising an aircraft as a long-range business jet.
The flight performances remain the same as that of the MRBJ/MRBJ-EA, such as cruise speed, stall speed, rate of climb and take-off/ landing distance. The reason behind this is very straightforward: the goal is to size an aircraft as much as possible similar to a midsize business jet. Furthermore, a diversion range of 150 km is considered, as most of the nominal aircraft range considers a fuel reserve dedicated to a diversion.

The payload estimate deserves a separate discussion, representing a fundamental aspect of the jet sizing. According to [39], the passengers and crew weight is chosen as follows:

- Crew: 85 kg for the pilot, co-pilot and flight attendant;
- Passengers: 85 kg for each.

Moreover, a maximum baggage weight of 50 kg is considered for each passenger. This led to a maximum payload of 1 690 kg, including 10 passengers with their baggage plus 4 crew members, 3 pilot and 1 flight attendant. A third pilot is considered since the flight's total duration is higher than 8 hours, and according to [25], a pilot must not exceed a total flight time of eight hours during twenty-four consecutive hours.

Once all the principal inputs are defined, the procedure to size and search for the most suitable solution can start. The method is henceforth explained: in the Airdata file, together with all the other inputs concerning the engine, structure and flight performance, a specific range value is imposed, just under 6 000 nmi, which corresponds to 11 102 km; subsequently, Hyperion is executed, obtaining the preliminary aircraft sizing that reflects the imposed constraints, and lastly, the range trend is calculated as the payload changes, printing a Payload - Range diagram.
Using this graph, it is possible to derive the range as the number of passengers changes; the goal remains to find an aircraft that can accommodate between 5 and 6 passengers for long-haul routes, i.e. more than 6 000 nmi. This value of the range is called as Design Range (DR).

Before presenting and discussing the results, it is essential to make a clarification about the MTOW: the value of the MTOW should fall within the category of MidSize Business Jets, i.e. approximately between 19t and 24t, with the objective of achieving a solution that has the flexibility and moderate size characteristics of a MidSize category but can also provide performance that falls into the Long-Range ones.

Five possible NBJ are shown in Table 3.8. It is possible to note the value of the range imposed, the number of passengers that remains constant and the MTOW of the solution. In addition, is present the payload feasible for 6 000 nmi derived from the corresponding payload-range diagram. Every payload corresponds to a precise number of passengers (plus their baggage); therefore, there is a further piece of information called 'Extra Payload', which corresponds to the difference between the payload that can be carried and the payload corresponding to the number of passengers that can be moved, taking into account their weight of 85 kg plus 50 kg of personal luggage. In this case, for the purpose of finding a solution as precise as possible, the objective of minimising the value of the Extra Payload is pursued.

MTOW [kg]	Pax	R [km]	Payload @ DR [kg]	Pax @ DR	Extra Payload [kg]
23 523	10	10 350	882	6 (810 kg)	70
23 310	10	10 250	820	6 (810 kg)	10
23 258	10	10 225	811	6 (810 kg)	1
23 070	10	10 150	766	5 (675 kg)	91
22 865	10	10 050	709	5 (675 kg)	34

Table 3.8: NBJ possible choices.

Following what has just been described, the third solution (the one underlined) is chosen, as it allows an adequate number of passengers, i.e. 6, to be carried over a distance of 6 000 nmi (or 11 102 km) while minimising the value of the Extra Payload. In Table 3.9 below, the range value for a number of passengers less than 6 is present, showing that it is possible to increase the distance by carrying fewer occupants. These range values have also been collected for the other solution and are present in Appendix A.

Pax	Payload [kg]	Crew [kg]	R [km]
5	675	340	11 327
4	540	340	11 533
3	405	340	11 617
2	270	340	11 637

Table 3.9: Range values at a specific number of passengers.

To conclude this part, the Payload-Range diagram of the final aircraft choice, i.e. the

NBJ, is present in Figure 3.4. Note that the maximum payload is 1 435 kg, corresponding to ten passengers plus one flight attendant.

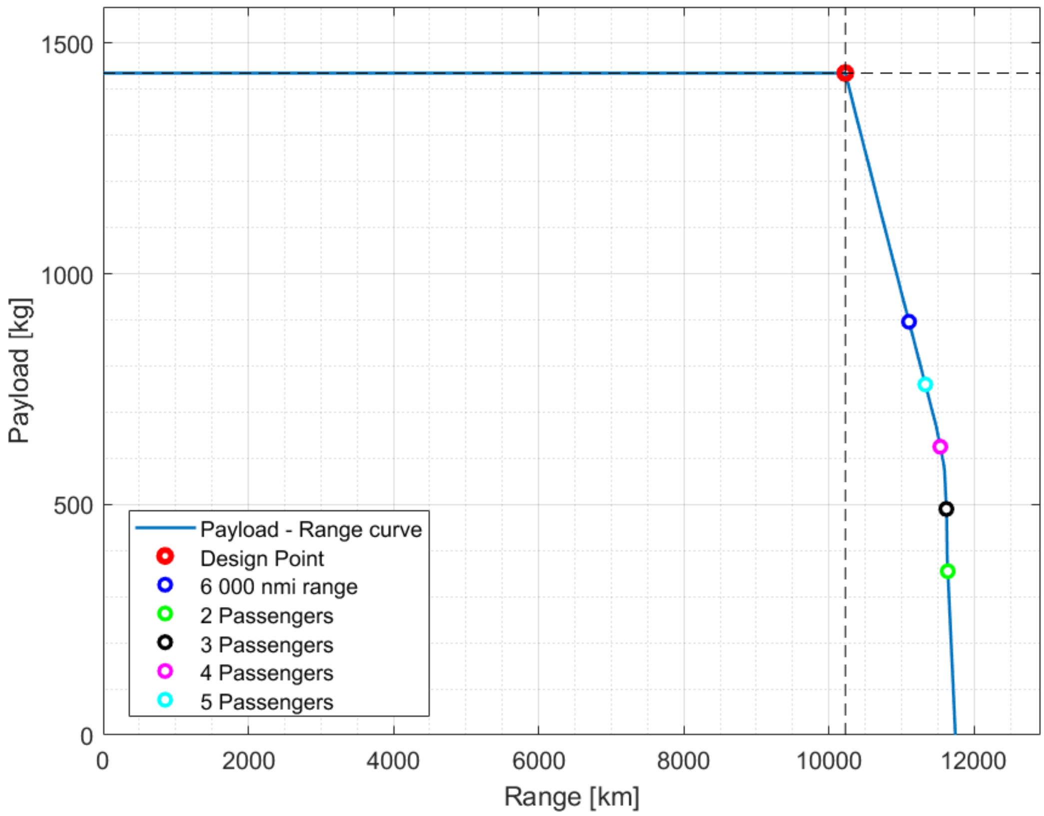


Figure 3.4: NBJ Payload - Range diagram.

To obtain the last leg of the Payload-Range graph, i.e. when the tank reaches its maximum capacity, it is necessary to obtain a preliminary estimate of the tank capacity. This value is estimated using an analytical formula present in [35], which takes into account the size of the wing. Therefore, the volume of the tank is 13.15 m^3. Considering the standard Jet A-1 Fuel with a density of 0.804 kg/L, the maximum fuel value by weight on board is 10 039 kg, taking into account that a 5 % of the volume is preserved for the variation of fuel density with temperature, since fuel tends to increase in density as temperature increases, thus increasing the volume occupied by the same quantity [33]. Lastly, the MTO - Range diagram of the NBJ is shown in Figure 3.5.

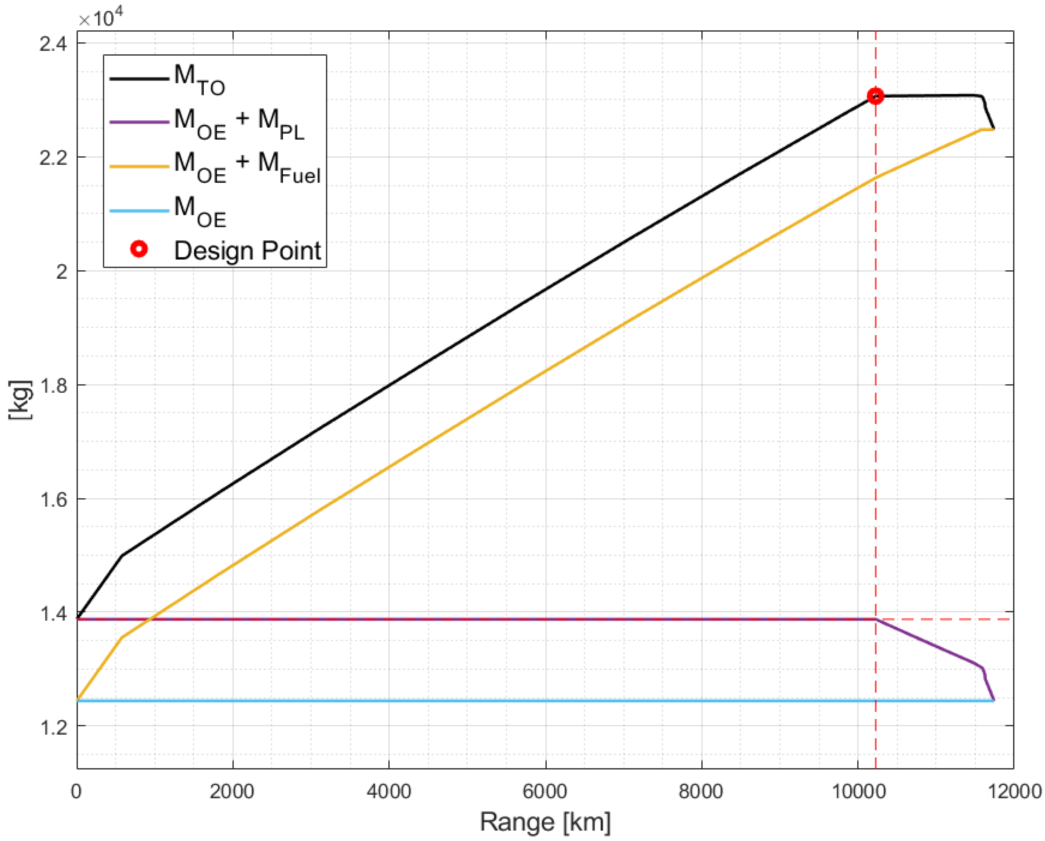


Figure 3.5: NBJ MTO - Range diagram.

3.1.4. Fuselage dimension sensitivity analysis

The size of the aircraft is a crucial aspect for preliminary aircraft sizing, not only because of the inherent weight involved, but to ensure adequate cabin space to accommodate the chosen layout and offer the greatest possible comfort. Hence, a brief sensitivity analysis on fuselage length and fuselage width is conducted, to explore if there is the possibility of improving the solution found in Section 3.1.3.

The fuselage length is a simple input in the aircraft Airdata file, whereas the fuselage width is computed, according to [42], after defining the number of aisles and seats abreast. The basic idea is to lengthen the fuselage and reduce the fuselage diameter and vice versa, so that the MTOW does not vary significantly. The formula used to calculate the fuselage width is shown herein in 3.1.

$$D_{fus} = Abreast \cdot 0.71 + Aisle \cdot 0.71 + 2 \cdot \Delta_{seat-fus} \tag{3.1}$$

The initial value for the aisle is 1 while the seats abreast is 2, considering a business jet seat, so more comfortable and voluminous. The distance from the lateral seat and the fuselage, i.e. $\Delta_{seat-fus}$, is set to 0.25 m. After that, these two values are tuned to obtain different solutions as listed in Table 3.10.

MTOW [kg]	Abreast	Aisle	D_{fus} [m]	L_{fus} [m]
23 438	2.15	1.15	2.84	18.73
23 385	2.10	1.10	2.77	19.23
23 316	2.05	1.05	2.70	19.73
23 258	2.00	1.00	2.63	20.23
23 165	1.95	0.95	2.56	20.73
23 067	1.90	0.90	2.48	21.23
22 963	1.85	0.85	2.42	21.73
22 837	1.80	0.80	2.34	22.23
22 712	1.75	0.75	2.28	22.73

Table 3.10: Result of fuselage dimension sensitivity analysis.

Moreover, Figure 3.6 helps to better understand the variation of MTOW according to fuselage length and diameter.

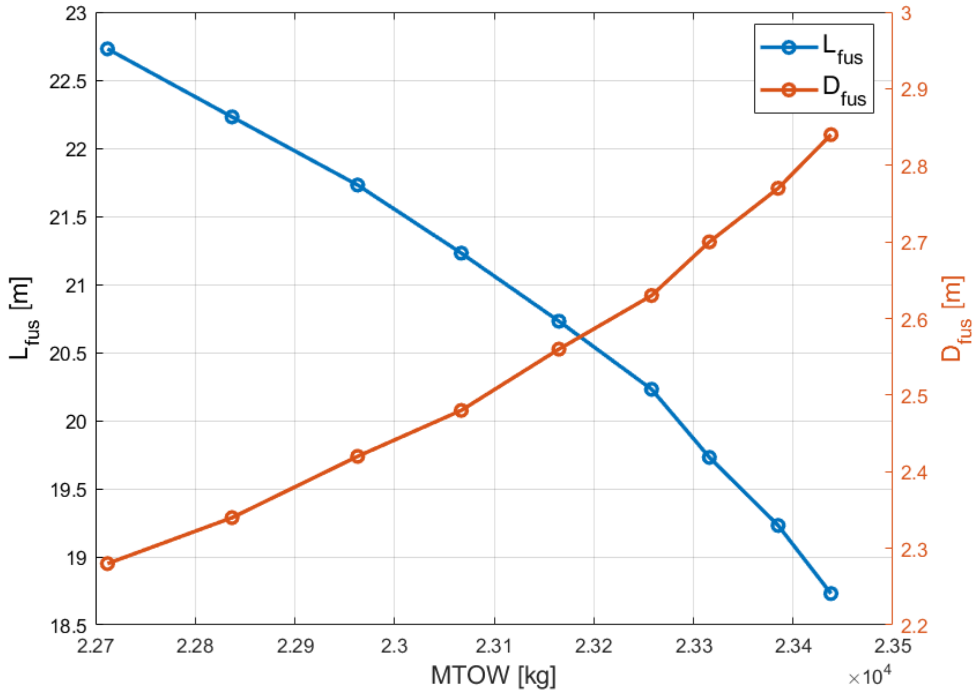


Figure 3.6: Variation of D_{fus} and L_{fus} Vs MTOW.

It can be observed that in the initial solution, the total fuselage width is around 2.63 m, a value slightly higher than the one present in the Dassault Falcon 2000, which is 2.34 m but referred only to the cabin width; therefore, according to [36] it is reasonable to subtract 1.5 in, corresponding to around 3.8 cm, for the fuselage skin thickness, leading to a total of 2.55 m for the cabin width (or internal diameter).

To understand whether the cabin width is suitable, brief research on the cabin dimension for some Business Jets is conducted; results are shown below in Table 3.11 where it can be deduced that the starting fuselage width appears to be oversized. The first three aircraft are MidSize, whereas the other three belong to the Long-Range category.

A/C Model	MTOW	w_{cab} [m]	h_{cab} [m]	L_{fus} [m]
Citation Longitude	17 917	1.96	1.83	22.30
Falcon 2000	19 414	2.34	1.88	20.23
Challenger 650	21 863	2.41	1.83	20.90
Falcon 8X	33 113	2.34	1.88	24.26
Global 5500	41 957	2.41	1.88	29.50
Gulfstream G650	45 178	2.49	1.91	30.40

Table 3.11: BJs cabin dimensions.

The table above shows that the cabin width value found, i.e. 2.55 m, is higher than the values generally used on board BJs, even in long-haul aircraft.
As a result of all the considerations just made, it is preferable to choose an aircraft with a smaller fuselage diameter in Table 3.10. The aircraft with an MTOW of 23 067 kg is selected as the final solution, which has a fuselage length increased by 1 m and a smaller diameter, compatible and in alignment with the data present in Table 3.11. This choice should not be a problem from the point of view of onboard comfort, presenting an appropriate cabin width and cabin height.

This solution also brings aerodynamic improvements. In fact, by approximating the fuselage to a cylinder, to simplify calculations, there is a reduction in the fuselage S_{wet} from 109.9 m^2 to 102.6 m^2, i.e. a reduction of 6.6 %.
The fuselage S_{wet} is directly linked to the aerodynamic fuselage drag. Hence, it is possible to estimate the variation in the aerodynamic fuselage drag coefficient, by exploiting the procedure illustrated in [37], leading to a reduction of $C_{D0_{fus}}$ from 0.0035 to 0.0033.

This change does not entail any relevant alterations to the aircraft's range, i.e. the Payload-Range graph remains unchanged. For the sake of clarity, the Payload-Range graph is present in Figure A.2 in Appendix A. To conclude, this final version of the NBJ permits to have an aircraft that is more aerodynamically efficient, preserving the comfort on board by using an adequate value of cabin dimensions.

3.1.5. Results

After conducting various analyses and sensitivity studies, the sizing of NBJ can be finalised, showing the results obtained. The inputs for the aircraft Airdata file are shown herein in Table 3.12, along with those used to size the MRBJ, to compare directly.

	MRBJ	NBJ
PC	980 kg	1 690 kg
$\mathbf{N_{pax}}$	6	10
$\mathbf{N_{pil}}$	2	3
$\mathbf{L_{fus}}$	20.23 m	21.23 m
$\mathbf{v_{EAS_{Stall}}}$	95 kn	95 kn
$\mathbf{v_{EAS_{HSC}}}$	245 kn	245 kn
$\mathbf{z_{HSC}}$	39 000 ft	39 000 ft
$\mathbf{ROC_{max}}$	4 350 ft/min	4 350 ft/min

	MRBJ	NBJ
$\mathbf{TO_{dist}}$	1 425 m	1 425 m
$\mathbf{LND_{dist}}$	810 m	810 m
$\mathbf{v_{EAS_{crs}}}$	200 kn	200 kn
$\mathbf{z_{crs}}$	45 000 ft	45 000 ft
R	7 408 km	10 225 km
BPR	4.5	6.5
$\mathbf{\Phi_{eng}}$	1.29 m	1.30 m
EPR	15.00	23.25

Table 3.12: Airdata input for the MRBJ and NBJ.

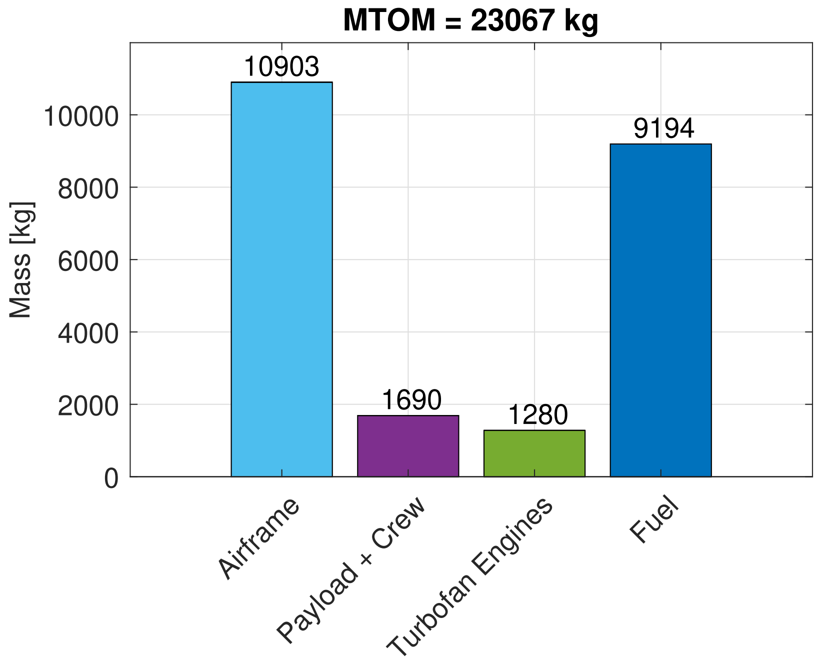
The payload changes, the increase in fuselage length and the engine improvements are easily visible. Before presenting other results, a clarification must be made regarding the difference in the number of passengers on board the two planes. The number of passengers used for the NBJ is obtained by considering that all seats are occupied, allowing performance for a lower number of occupants to be derived backwards. In contrast, for the MRBJ, the number of passengers is related to the performance (i.e. range) on the manufacturer's official website [3].
The mass breakdown and performance results obtained by Full Sizing using Hyperion are shown in Table 3.13, comparing with the ones from the MRBJ.

	MRBJ	NBJ	Δ [%]
$\mathbf{M_{TO}}$	19 852 kg	23 067 kg	+ 16.2
$\mathbf{M_{empty}}$	11 018 kg	12 183 kg	+ 10.6
$\mathbf{M_{af}}$	9 826 kg	10 903 kg	+ 11.0
$\mathbf{M_{pc}}$	980 kg	1 690 kg	+ 72.4
$\mathbf{M_{eng}}$	1 192 kg	1 280 kg	+ 7.4
$\mathbf{M_{fuel}}$	7 854 kg	9 194 kg	+ 17.0

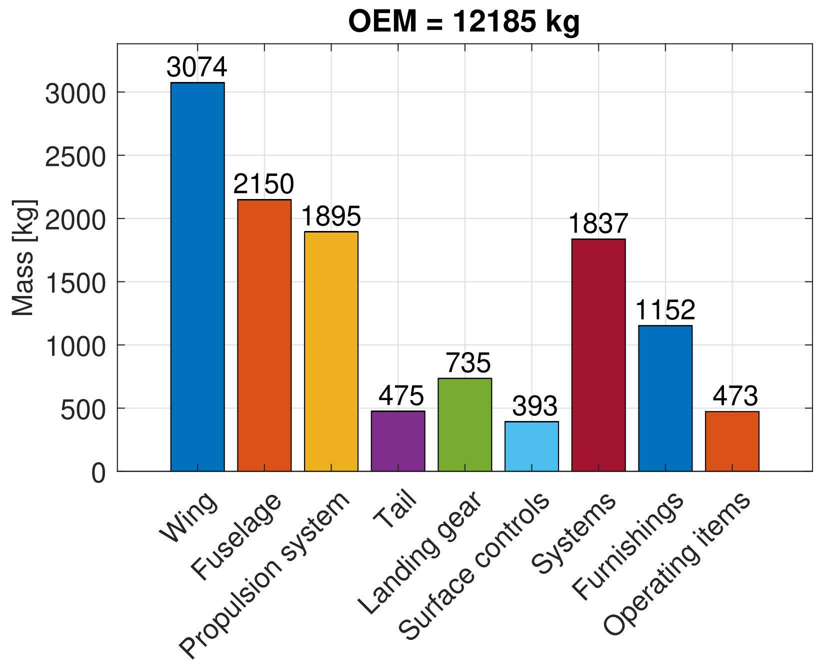
	MRBJ	NBJ	Δ [%]
S	65.7 m^2	76.1 m^2	+ 15.8
b	24.7 m	26.6 m	+ 7.7
$\mathbf{C_{D_0}}$	0.0199	0.0190	- 4.5
R	7 408 km	10 225 km	+ 38.0
$\mathbf{FT_{TOT}}$	10h 6m	13h 17m	+ 31.5
$\mathbf{T_{max}}$	59.5 kN	63.7 kN	+ 7.1

Table 3.13: Hyperion output for the MRBJ and NBJ.

Concerning the masses breakdown and comparing to the MRBJ results, it is notable that there are slight increments in the airframe and engine weights, whereas the most marked difference can be seen in the transported fuel (+ 17.0 %), as the range increases by around 38 %. As expected, using innovative engines means the fuel difference is not so marked. Furthermore, there is an increment in the wing surface due to the higher MTOW. Figure 3.7 helps to visualise the masses breakdown better and analyse the airframe components in more detail.



(a) MTO breakdown.



(b) Airframe mass breakdown.

Figure 3.7

A significant result that comes from the aircraft sizing is the Sizing Matrix Plot. The graph, shown in Figure 3.8, helps to assess some fundamental characteristics, such as the wing surface and thrust necessary, through the selection of the design point, expressed in terms of wing loading W/S and thrust-to-weight ratio T/W. It is visible that the more stringent constraints are the landing distance and climb requirements in OEI conditions. For the sake of clarity, the design point is shown herein:

- Wing Loading: 2 969.0 N/m^2
- Thrust-to-Weight ratio: 0.273

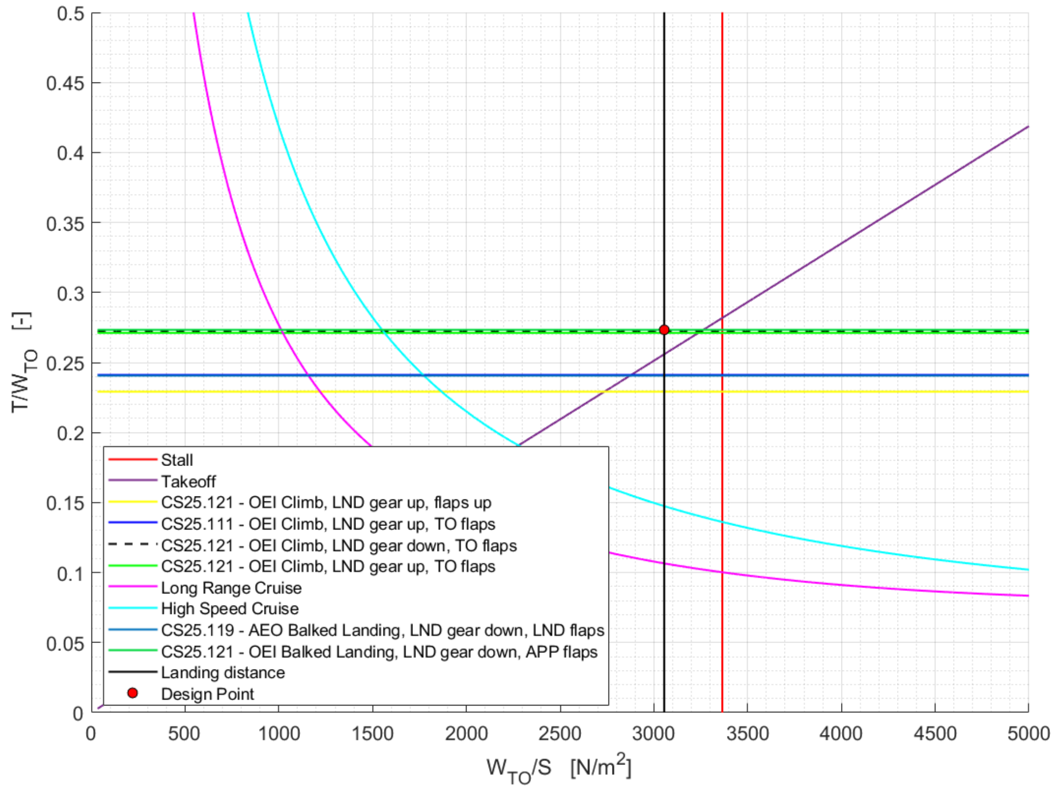


Figure 3.8: NBJ Sizing Matrix Plot.

The last part of this section is dedicated to presenting some flight parameters. In particular, Figure 3.9 shows a subplot of various flight parameters about the sizing mission, where it is notable in some graphs an abrupt change of them due to the diversion manoeuvre.

In conclusion, two other graphs related to turbofan thrust, engine throttle and tank level trend are presented in Figure 3.10 and Figure 3.11. A last clarification about the tank level trend: it starts at a value of 100, i.e. full tank, and ends at a value of 2.5; this is

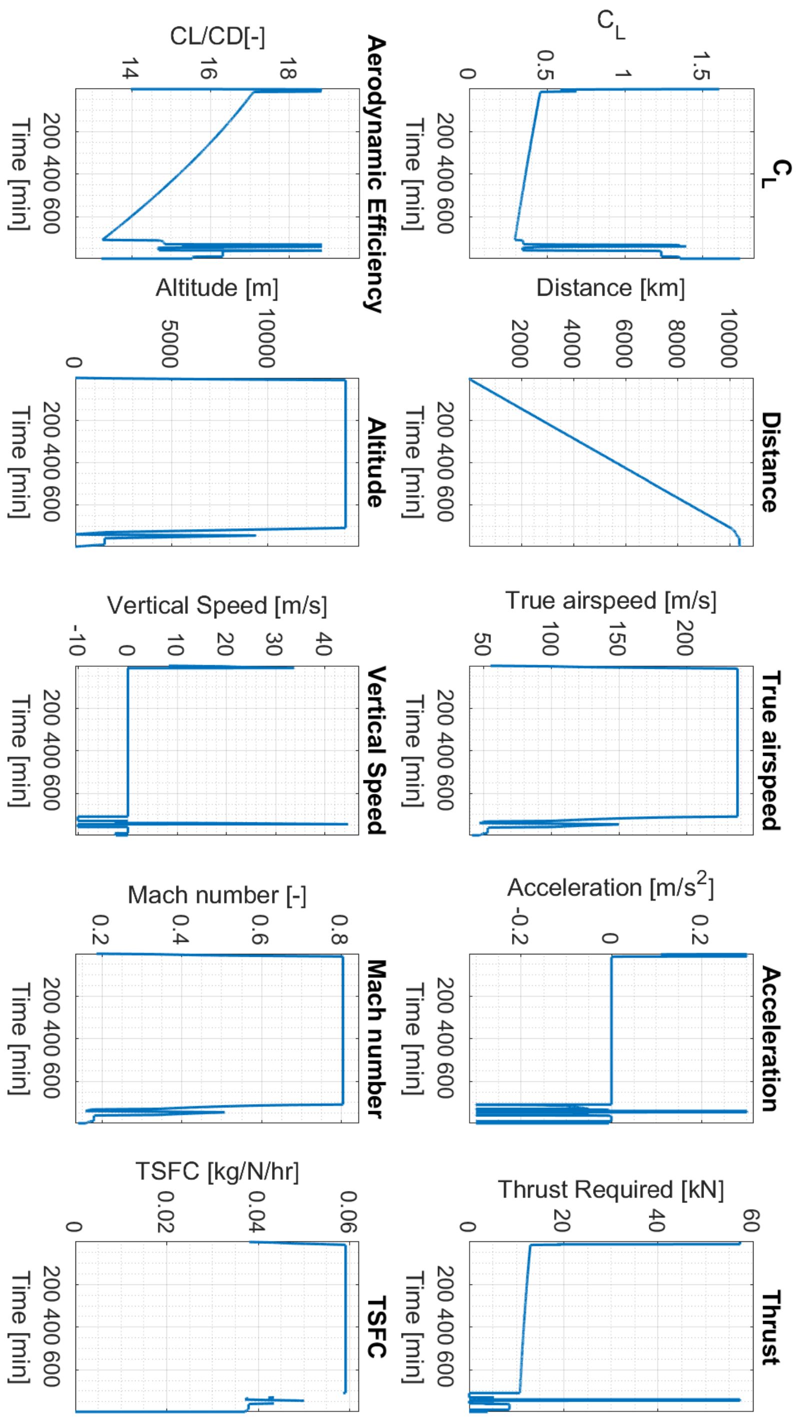


Figure 3.9: NBJ Flight parameters.

because a reserve of 2.5 % fuel is guaranteed for each mission, also for safety reasons.

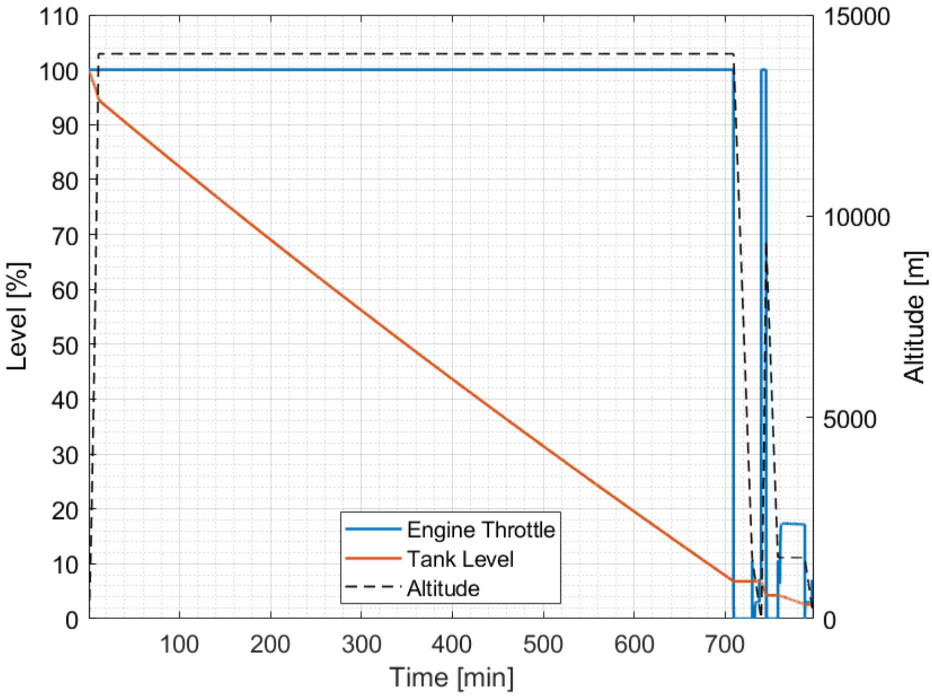


Figure 3.10: Engine Throttle and Tank Level variation.

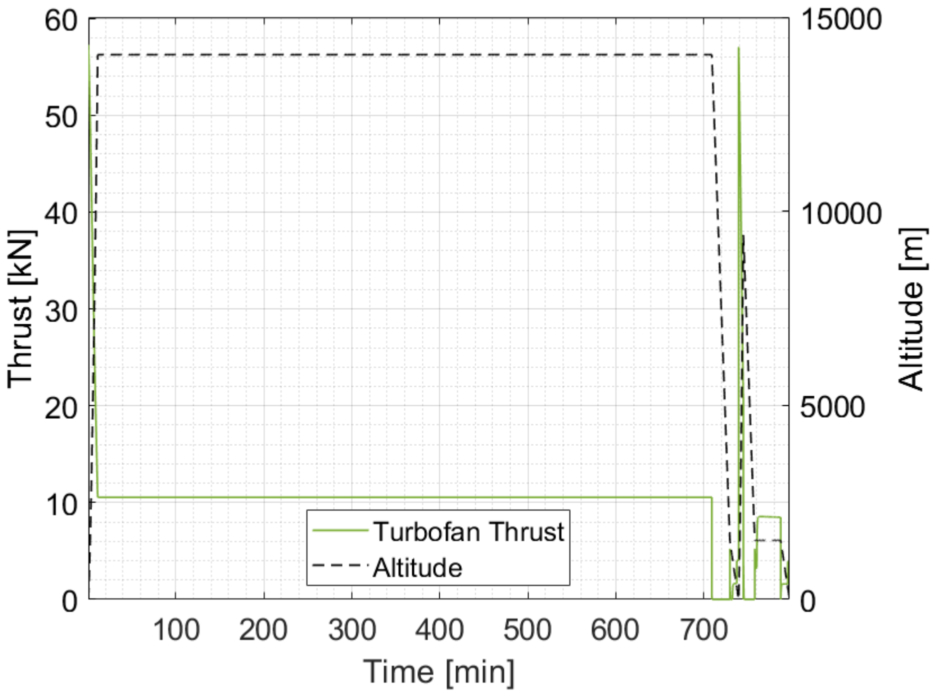


Figure 3.11: Turbofan Thrust variation.

3.2. Cost Analysis

A preliminary estimation of the operating costs of an aircraft is crucial whenever a new solution is proposed to the market. The results are essential not only for the manufacturer, but also for the possible future customer. Obviously, every aircraft manufacturer has its method for obtaining all recurring and non-recurring aircraft operating costs in detail; however, these methods are almost always confidential. To overcome this problem, three different types of models for calculating Direct Operating Costs are proposed, analysed and compared, and finally choosing the most suitable one, which is used for the calculation of costs within the mission scenarios.
Before presenting the different methodologies used, an estimation of the cost of the aircraft is presented, assuming that a certain amount of aircraft will be produced in the future when it is launched on the market.

3.2.1. Aircraft cost estimation

The cost of an aircraft is a key element in deciding whether to engage in a new aircraft programme, i.e. is a sort of ultimate driver. There must be a real balance between technological innovation and associated costs: a highly innovative project requiring huge expenditure will never be considered. Hence, a methodology to compute the cost of developing, manufacturing, testing, operation and disposal is presented, providing essential information for calculating the Ownership or Capital Direct Cost.

The model used to achieve the aeroplane cost is called the "Eastlake Model", coming from [31] and explicitly built for Business Aircraft. Through the calculation of the man-hours for the manufacturing, tooling, engineering and flight testing, it is achievable to derive the associated cost by multiplying the hours by the respective hourly rates. These last pieces of information are used in accordance with [33] and [2], and referred to 2012.
The model inputs various parameters, from aircraft performance and technical data to material and economic factors. Regarding the aeroplane performance entries, the data are present in Section 3.1.5. Moreover, it is necessary to impose an aircraft quantity to be produced within a certain period, in this case set to 10 years and an aircraft quantity devoted to the flight test campaign. With regard to the A/C amount for FT, the number is appropriate and in line with what occurred during the design of the Dassault Falcon 7X [1], i.e. 3 aircraft, whereas the number of aircraft to be produced in 10 years is set to 250.

Before presenting the results, two other crucial aspects have to be mentioned. The first is a material consideration; in fact, the choice of the material for the airframe significantly impacts the manufacturing cost, not only due to the price but also to the different industrial processes that each material requires specifically. To solve this challenge, Raymer [33] proposes a material cost factor, taking aluminium as a reference, as it is the most spread in the aeronautic sector and, therefore, the associated cost is easily predictable. The material factors range updated to 2012 and the values selected for the Business Aircraft are shown in Table 3.14.

Material	**f_{mat}**	**Mat. %**
Aluminium	1.00	25 %
Carbon-Epoxy	1.45	45 %
Fiberglass	1.15	5 %
Steel	1.75	10 %
Titanium	1.45	15 %

Table 3.14: Material factor and relative weight.

The decision for the NBJ is to adopt a significant percentage of composite material. This choice aligns with the latest modern airliners (e.g. Boeing 787 Dreamliner, Airbus A350 XWB) and business aircraft like the new Dassault Falcon 10X [41][10].

Following the procedure presented in [2] and, since the airframe is a union of different materials, the final material factor is a combination of each material cost factor, taking into account the corresponding relative weight in percentage. This resulting factor is applied to all the development man-hours and all the specifications are displayed in Table 3.15 below.

Sector	**Rate**
Engineering	115 USD
Tooling	118 USD
Quality Control	108 USD
Manufacturing	98 USD

Table 3.15: Hourly rates in 2012 U.S. dollars.

The second aspect examined is the economic one; inflation is considered to bring costs up-to-date, particularly for the hourly rates for engineering, manufacturing, tooling and quality control. The inflation rate between 2012 and 2022 was around 12 %, therefore the cost is affected by an inflation factor f_{inf}. In addition, since in the model U.S. dollars

(USD) are used, a conversion factor is needed to convert into Euro (EUR) by using the average exchange rate in March 2023. These two factors are herein shown:

$$f_{inf} = 1.12 \quad \text{and} \quad f_{usd2eur} = 0.92$$

In conclusion, the cost of research, development, testing and engineering, named C_{RDTE}, along with total aircraft cost and purchase price, are presented below in Table 3.16. The purchase price considers the addition of the sales margin and spare parts factor; the sales margin is generally covered by industrial secrecy and may vary from one company to another, thus for this methodology is set at 15 %, which should be a good approximation for this aircraft category. Lastly, the spare parts and other services are usually included in the aircraft purchase price. According to [2], this value is difficult to obtain and is assumed to be 10 %.

	Value
C_{RDTE} [€]	9 453.4 M
C_{AC} [€]	37.9 M
P_{AC} [€]	48.0 M

Table 3.16: NBJ Cost and Price.

One aspect that has not yet been addressed is the variation of the aircraft production cost according to the number of units produced in a specific time frame. In the results just shown, a value of 250 units to be produced within 10 years is imposed, which is reasonable and in line with the numbers in the BJs sector. To better understand the correlation between total production costs incurred and units produced, Figure 3.12 helps to visualise the concept more clearly. Indeed, it can be noticed that costs decrease as the number of aircraft produced increases, reaching a moderate variation for a high number of aircraft delivered, i.e. more than around 500 units.

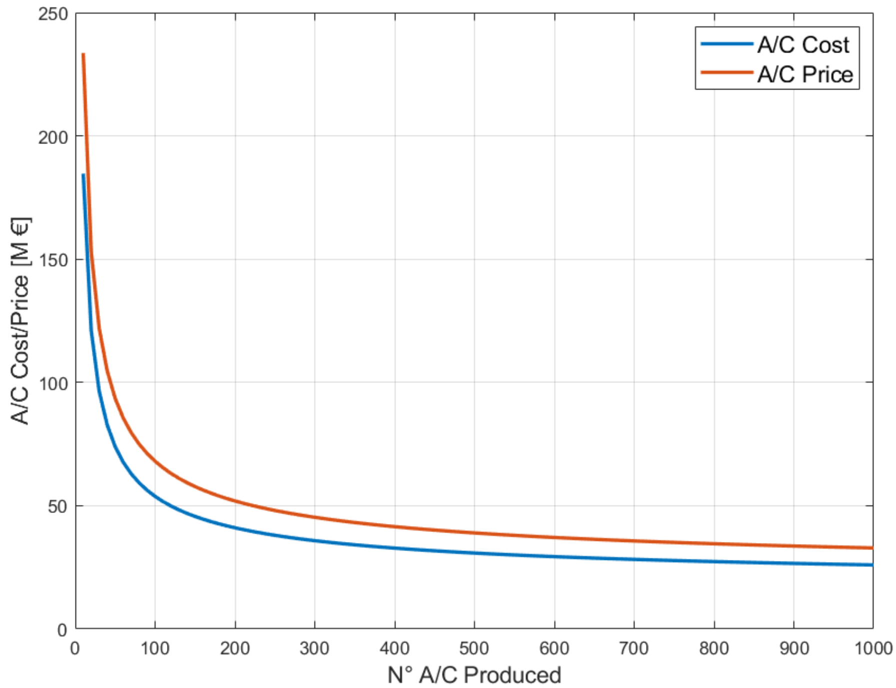


Figure 3.12: Variation of A/C Cost/Price Vs A/C quantity produced.

3.2.2. DOC estimation methodologies

The computation of Total Operating Costs (TOC) is a vital step for the aircraft's operator, as it gives information on profitability and marketability. Moreover, it permits the estimation of the Ticket Price, which is very helpful in comparing the proposed solution with those already on the market. Commonly, the TOC is split into Direct Operating Cost (DOC) and Indirect Operating Cost (IOC). According to [2], DOC includes all aircraft and traffic-related costs:

- Fuel;
- Maintenance: engine and airframe;
- Crew expenses;
- Fees: flight fees for landing and navigation, ground handling and airport fees;
- Ownership.

Instead, the IOC incorporates all the aircraft costs not strictly related to a single flight and can be considered a complement of DOC. It includes, in accordance with [16], numerous cost elements such as sales, administration, general management, property cost, accounts etc. Naturally, there are several other costs involved in the aircraft operation, such as catering, advertising, cancellation expenses etc., but they are not considered since they have a minor impact on TOC and, in addition, they require more inputs, difficult to guess at the initial stage of aircraft design.

At this stage, three different DOC models are adopted, allowing all the cost items taken into account to be derived clearly and unambiguously, then making a brief comparison and finally choosing the most suitable model to be used in the Scenario Analysis. The models are listed herein:

- **TU Berlin**: published in 2013 and born in the Technische Universitat Berlin, it is one of the most up-to-date models.
- **AEA (Association of European Airlines)**: published in 1989, is still a reliable method to evaluate the DOC.
- **UNIFIER-19 Project**: method used for evaluating the DOC for a 19-seater aircraft, combines methods from TU Berlin and Gudmundsson [31].

Three different references are considered to set up DOC models correctly: information present in CeRAS [34] (Central Reference Aircraft data System) are used for the TU Berlin method, the AEA Method is accomplished following the procedure illustrated in [18], whereas the UNIFIER-19 Method (called for brevity as UN19) is directly achieved from it [2].
These three methods input the same data, such as:

- Aircraft performance data: range, total flight time, fuel burnt;
- Aircraft weight and payload: TOM, OEM, Engine weight, number of passengers and number of seats;
- Aircraft cost;
- Real values of navigational and airport fees, fuel price and crew salary.

The outputs are expressed in terms of DOC per year, DOC per flight and DOC per hour. Furthermore, operational expenses, known as OPEX, is calculated along with a "baseline" ticket price. The following paragraphs present and compare the five main items of Direct Cost plus some flight information for the three models, highlighting the differences.

DOC Model data. This short paragraph illustrates the computation of Flight Cycle (FC) and Block Time (T_{block}). The Block Time, by definition, is the time from doors closing at the departure airport to doors opening at the destination. In this case, a supplement time of 10 minutes at each airport for the taxi is assumed, yielding:

$$T_{block} = T_f + 0.33 \tag{3.2}$$

Concerning the Flight Cycle, is expressed as the number of typical missions the aircraft performs annually, excluding maintenance, block time supplement and other restrictions. The TU Berlin (TUB) method computes FC as follows:

$$FC_{TUB} = \frac{POT - DT}{BTS + T_{block}} \tag{3.3}$$

Where POT (Potential Yearly Operation Time) = 7 300 hr (18hr x 365 gg), BTS (Block Time Supplement per flight) = 1.83 hr and DT (Yearly Forced Downtime) = 2748.8 hr composed by C-Checks, D-Checks, Repairs and Night Curfew [34].
The UN19 uses the formula from AEA to get the Flight Cycle:

$$FC_{AEA} = \frac{3750}{T_{block} + 0.5} \tag{3.4}$$

Fuel cost. It is calculated in the same manner for the three methods by a simple multiplication:

$$DOC_{fuel} = C_{fuel} \cdot BF \cdot f_{usd2eur} \tag{3.5}$$

The BF (Block Fuel) is the fuel consumed in a flight, the fuel price C_{fuel} depends on several parameters depending on the country, refuelling service, airport etc.; hence, the IATA average fuel price for Europe is considered. On 17 March 2023, the price of Jet-A1 fuel was 236.51 cts/gal, which translates into 0.796 \$/kg.

Crew cost. The pilot's and flight attendant's costs are calculated approximately similarly. TUB Model considers an annual salary for the pilots, first officer and flight attendant, leading to:

$$DOC_{crew} = cc \cdot (S_p \cdot N_{pil} + S_{fo} \cdot N_{fo} + S_{fa} \cdot N_{fa}) \cdot f_{usd2eur} \tag{3.6}$$

The S_p (Pilot salary) = 200 000 €, S_{fo} (First officer salary) = 160 000 € and S_{fa} (Flight attendant salary) = 85 000 €. Instead, the AEA and UN19 Methods consider the crew salaries per flight hour; thus, DOC_{crew} is computed as follows:

$$DOC_{crew} = cc \cdot (S_{p_h} \cdot N_{pil} + S_{fo_h} \cdot N_{fo} + S_{fa_h} \cdot N_{fa}) \cdot T_{block} \tag{3.7}$$

In accordance with [2], S_{p_h} = 65 €/hr, S_{fo_h} = 55 €/hr and S_{fa_h} = 40 €/hr. In the two formulae just illustrated, there is the item "Crew Complement" (cc): the number of full crew needed for an aircraft for a normal continuous operation, respecting the maximum flight hour limitation, vacations, training and medical checks. In this case is set to 4.

Ownership cost. To achieve the Ownership or Capital cost contribution, the three methods use different formulas but share a few inputs, such as: Depreciation Period (DP) set to 15 years, Interest Rate (IR) set to 5%, Insurance Rate (f_{ins}) set to 0.005 and the Residual Value Factor (f_{rv}) set to 0.1.

The AEA and UN19 Model share the same method for estimating DOC_{own}; it can all be summed up in an expression that combines three different terms, which are: depreciation, which represents the periodic conversion of a fixed asset into an expense, i.e. the distribution of an item's value reduction over the service life, interest cost, assuming that the new aircraft is financed entirely from outside sources and the insurance cost, considered a percentage of the aircraft price. The equation is herein shown:

$$DOC_{own} = P_{ac} \cdot \left[IR \cdot \frac{(1+IR)^{DP} - f_{rv}}{(1+IR)^{DP} - 1} + f_{ins} \right] \tag{3.8}$$

Lastly, the TUB Methods consider inputs such as the price per kg of OEM and the price per kg of the engine, along with the estimation of the annuity rate. The formula is expressed below:

$$DOC_{own} = [P_{OEM} \cdot (M_{empty} - N_{eng} \cdot M_{eng}) + P_{ENG} \cdot M_{eng} \cdot N_{eng}] \cdot (a + f_{ins}) \tag{3.9}$$

Where P_{OEM} = 3 500 \$/kg, P_{ENG} = 5 000 \$/kg and the annuity rate is computed as follow:

$$a = IR \cdot \frac{1 - f_{rv} \cdot (\frac{1}{1+IR})^{DP}}{1 - (\frac{1}{1+IR})^{DP}} \tag{3.10}$$

Maintenance cost. Aircraft maintenance is a fundamental aspect that must be considered when acquiring the aircraft, as it covers a significant share of the annual operating costs. The methods used in this work adopted different ways to estimate direct maintenance cost; thus, each model is treated singularly.

- *TUB*: the maintenance DOC is split into three terms:
  - Airframe material, based on OEM and computed as follows:

$$DOC_{man,af} = \frac{M_{empty}}{1000} \cdot (0.21 \cdot T_{block} + 13.7) + 57.5 \tag{3.11}$$

  - Airframe personnel, based on Labour Rate (LR) and Burden factor (B) that includes airline overhead, the cost of acquiring, building, facilities, maintenance tools and other indirect costs [15], computed as follows:

$$\begin{aligned} DOC_{man,per} = LR \cdot (1+B) \cdot \Bigg[&(0.655 + 0.01 \cdot \frac{M_{empty}}{1000}) \cdot T_{block} + \\ &+0.254 + 0.01 \cdot \frac{M_{empty}}{1000} \Bigg] \end{aligned} \tag{3.12}$$

    The Labour Rate (LR) = 60 €/hr and Burden factor (B) = 4 [34].

  - Engine, calculated taking into account the number of engines (N_{eng}) and the sea level static thrust ($T_{SL,static}$):

$$DOC_{man,eng} = N_{eng} \cdot (1.5 \cdot T_{SL,static} + 30.5 \cdot T_{block} + 10.6) \tag{3.13}$$

- *AEA*: the method account for three terms, which are the cost of labour per hour ($C_{mainLab}$), the cost of maintenance parts per hour ($C_{mainParts}$) and the maintenance man hours per flight hour (f_{ease}), leading to:

$$DOC_{man} = (f_{ease} \cdot C_{mainLab} + C_{mainParts}) \cdot U \tag{3.14}$$

  The f_{ease} is obtained with the following equation, where U is the Utilization Rate and is the multiplication of the Flight Cycle (FC) times the Block Time (T_{block}).

$$U = FC \cdot T_{block} \tag{3.15}$$

- *UN19*: the method proposed is derived from [31] and accounts for airframe and engine maintenance, overhaul (OH) and hot section inspection (HSI) work. These components are now clarified:

- Airframe and engine cost, Gudmundsson proposes the following formula where F_{mf} is the "ease of maintenance" factor obtained from [2] and LR in the Labour Rate previously treated:

$$DOC_{man,af-eng} = F_{mf} \cdot LR \cdot T_{block} \tag{3.16}$$

- Engine overhaul cost, achieved by the following equation:

$$DOC_{OH} = N_{eng} \cdot \left(\frac{P_{OH}}{TBO_{OH}} \right) \cdot T_{block} \tag{3.17}$$

  Where the Time Between Overhaul (TBO_{OH}) = 6 000 hr and Price for Overhaul (P_{OH}) = 600 000 \$.

- Hot Inspection cost, from this expression:

$$DOC_{HSI} = N_{eng} \cdot \left(\frac{P_{HSI}}{TBO_{HSI}} \right) \cdot T_{block} \tag{3.18}$$

  Where the Time Between Overhaul (TBO_{HSI}) = 2 500 hr and Price for Overhaul (P_{HSI}) = 180 000 \$.

Fees cost. The contribution of fees to direct costs depends on multiple factors; first, the geographical region where the flight is operated is determinant and second, the amount of taxes increases as the services required at the airport of departure and arrival increase. This cost element can be subdivided into three parts for all the methods. Navigational fees are the first to be analysed and comprise the route navigation fees, depending on the flight zone; in this work, the EUROCONTROL zone is considered as it this the body that manages the navigation fees in the European Union countries. The second subpart is related to Ground Handling and depends on the aeroplane TOM and the airport, whereas the third contribution is the Terminal fees, depending again on the airport and number of passengers transported; it includes cost elements such as security and boarding services. Naturally, there are numerous other fee items (freight loading charges, loading bridges service, assistance to PRMs etc.); nonetheless, they do not have such a significant contribution and require further specific input, so they are neglected.
The three models use different methodologies to compute the Navigation, Terminal and Ground Handling fees, thus they are treated singularly.

- *Navigation*: the TUB, AEA and UN19 methods use the same equation to achieve this contribution:

$$DOC_{fees,nav} = K_{nav} \cdot \left(\frac{R}{100}\right) \cdot \left(\frac{M_{TO}}{50}\right)^{0.5} \tag{3.19}$$

Where $K_{nav} = 56.6$ € is the Unit Rate of Charge, updated and published by EUROCONTROL for each European country [27]. In this case, an average value is considered.

- *Ground Handling and Landing*: this contribution is calculated in the same way by AEA and TUB methods, and it depends only on the Landing Aircraft Mass:

$$DOC_{fees,ground} = 2 \cdot K_{lnd} \cdot M_{TO} \tag{3.20}$$

Where $K_{lnd} = 5.21$ €/ton is the Landing reference price, coming from the 2023 Regulated Charges for SEA Airports (Milan Linate and Milan Malpensa) updated in January [40]. On the other hand, the Unifier-19 method uses a different approach, considering a different rate:

$$DOC_{fees,ground} = K_t \cdot \left(\frac{M_{TO}}{50}\right)^{0.7} \tag{3.21}$$

Where $K_t = 170$ € is the Terminal reference price according to [2].

- *Terminal and Airport services*: this fee term is treated differently by the various methods, but always concerns the services offered by the arrival airport. TUB propose a dependence only on the payload mass:

$$DOC_{fees,ap} = K_{gr} \cdot M_{pl} \tag{3.22}$$

Where $K_{gr} = 0.15$ €/kg is a ground reference price coming from [34]. Instead, AEA takes into consideration the airport/terminal fees, hence:

$$DOC_{fees,ap} = (K_{pax} + K_{sec}) \cdot N_{pax} \tag{3.23}$$

Where $K_{pax} = 17.14$ €/pax is a passenger charge reference price and $K_{sec} = 2.48$ €/pax is a passenger security service reference price; both coefficients are directly retrieved from 2023 Regulated Charges for SEA Airports. Lastly, UN19 compute this term similarly to AEA, but adds an extra term due to the Aircraft Mass, as shown below:

$$DOC_{fees,nav} = (K_{pax} + K_{sec}) \cdot N_{pax} + 2 \cdot K_{lnd} \cdot M_{TO} \tag{3.24}$$

Where the coefficients have the values illustrated above.

OPEX and Indirect Operating Cost

The Operational Expenses, i.e. OPEX, include all the expenses incurred through normal business operations. Within the context of this work, OPEX is essentially the sum of all Direct Costs except for the Ownership or Capital one. In other words, it can be expressed by the herein equation:

$$OPEX = DOC_{man} + DOC_{fees} + DOC_{crew} + DOC_{fuel} \tag{3.25}$$

Operational Expenses are particularly interesting when looking at their value in relation to flight hours or the flight itself, allowing a better understanding of the operating costs of running that route.

On the other hand, the Indirect Operating Cost (IOC) includes all the costs not strictly related to a single flight, i.e. may include elements such as sales, customer services, marketing, administration and overhead [44]. Since its values depend on how an airline/company decides to run its operation, the estimation may be arduous by simple statistical analysis. According to [33], IOC can vary between one-third to be equal to DOC. Therefore, to simplify the calculation in this work, the Roskam [38] estimation is considered; indeed, it assumes that IOC are a fraction of DOC, as expressed by the following equation:

$$IOC = f_{IOC} \cdot DOC_{TOT} \tag{3.26}$$

where the factor f_{IOC} is proportional to the inverse of block distance and is set to 0.55.

Ticket Price estimation

The cost of an airline ticket is one of the primary decision elements when a customer decides whether to fly with that airline. Its value allows both to cover the operational expenses to execute that flight and to derive a profit margin from allowing the business to continue. Indeed, it is possible to divide the ticket price into two main components: a "baseline" ticket price, covering all the operational expenses, and a sales margin that allows the company to make a profit. The last term could vary from one company to another and generally is expressed as a percentage of baseline ticker price, ranging from 2 to 10 %. Due to the difficulty in obtaining precise information on the 'sales margin', in this paper, only the 'baseline' ticket price is considered, obtained by dividing the DOCs referring to the single flight for the number of seats available. The equation below expresses what has just been stated:

$$P_{tkt_{base}} = \frac{DOC_{TOT_{flight}}}{N_{seats}} \tag{3.27}$$

A detailed analysis of the actual cost of an airline ticket is neglected due to the difficulty in estimating economic and financial parameters specific to each flight company. In fact, each airline ticket may differ from another for the same flight, and the reasons for this are particularly far-reaching and not inherent to this work.
Notwithstanding, the value of the "baseline" Ticket Price permits an immediate comparison between the proposals illustrated later.

3.2.3. Discussion of results

In this section, the results obtained for the NBJ using the three DOC Methods are presented, analysing in detail the Direct Cost, the Operational Expenses and the "baseline" Ticket Price. Successively, based on them, only one model is selected against which the NBJ, MRBJ and LRBJ are be compared. The LRBJ is a long-range business jet obtained through a Clean Sheet sizing of the Dassault Falcon 8X; the results of this sizing are illustrated in Table A.6 and Figure A.6, in Appendix A. Furthermore, this model is used to calculate costs within the scenarios presented in Section 3.3.

Model comparison results

The results are obtained using the three DOC Methods for the NBJ by imposing the sizing mission of 10 225 km with a total payload mass of 1 690 kg, including baggage and crew members. The Block Time (T_{block}) used is the same for all methods, where the Flight Cycle (FC) differs from one model to another since it is an estimation. The two parameters are shown herein in Table 3.17:

	Value
T_{block}	13h 37m
FC_{TUB}	295
FC_{AEA}	266

Table 3.17: NBJ FC and T_{block}.

Table 3.18 presents the annual DOC for the NBJ, obtained by multiplying the DOC_{TOT} by the Flight Cycle (FC), along with the IOC. Moreover, a graphical representation of the single DOC items is present in Figure 3.13.

	TUB	AEA	UN19
DOC_{fuel} [€]	1 979 900	1 784 800	1 784 800
DOC_{crew} [€]	2 580 000	2 966 100	2 966 100
DOC_{own} [€]	4 495 800	4 644 300	4 644 300
DOC_{main} [€]	1 324 000	1 519 300	1 823 000
DOC_{fees} [€]	1 288 700	1 152 600	1 178 300
DOC_{TOT} [€]	11 668 000	12 067 000	12 397 000
IOC [€]	6 417 700	6 636 900	6 818 100

Table 3.18: DOC methods comparison.

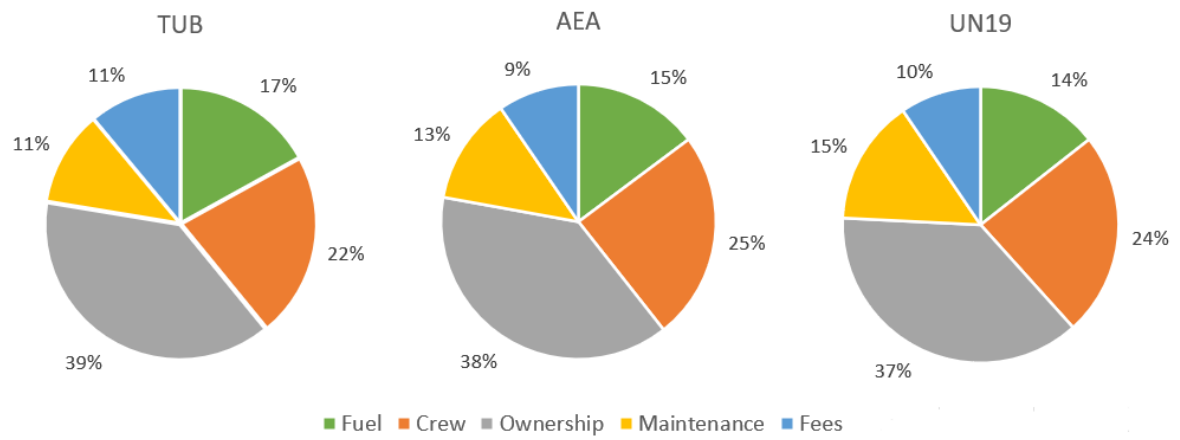


Figure 3.13: DOC methods comparison.

It is notable that all the DOC items are similar, except for the maintenance one, since each model proposes a different estimation procedure. Concerning the Operational Expenses, they are illustrated in Table 3.22, referring them to the year, single flight and flight hour.

	TUB	**AEA**	**UN19**
$OPEX_{year}$ [€]	7 172 600	7 422 700	7 752 300
$OPEX_{flight}$ [€]	24 336	27 939	29 179
$OPEX_{hour}$ [€]	1 787	2 052	2 143

Table 3.19: DOC Models: OPEX comparison.

To conclude, the baseline Ticket Price achieved through the models is presented in Table 3.20 below.

	TUB	**AEA**	**UN19**
$P_{tkt_{base}}$ [€]	3 959	4 541	4 666

Table 3.20: DOC Models: Baseline Ticket Price comparison.

Operating Expenses comparison between aircraft

The results gained using one DOC method for three different aircraft is presented in this last paragraph. The aircraft are the NBJ, MRBJ and LRBJ, where the following sizing missions are considered:

- NBJ: range = 10 225 km, payload = 1 690 kg (10 pax + 4 crew);
- MRBJ: range = 7 408 km, payload = 980 kg (6 pax + 2 crew);
- LRBJ: range = 11 945 km, payload = 1 420 kg (8 pax + 4 crew).

The data employed for the MRBJ and LRBJ are retrieved directly from the Dassault Aviation site [3]. The DOC method selected is the UN19 one since it combines an AEA and Gudmundsson model with more accuracy and detail in some items, such as maintenance and fees direct costs. The results are herein illustrated in Table 3.21 only for the annual DOC and in a graphical way in Figure 3.14.

	MRBJ	NBJ	LRBJ
DOC_{fuel} [€]	1 923 000	1 784 800	2 291 100
DOC_{crew} [€]	2 075 300	2 966 100	2 979 300
DOC_{own} [€]	4 325 000	4 644 300	7 245 300
DOC_{main} [€]	1 803 400	1 823 000	2 456 100
DOC_{fees} [€]	1 036 400	1 178 300	1 400 000
DOC_{TOT} [€]	11 163 000	12 397 000	16 372 000

Table 3.21: Aircraft DOC comparison.

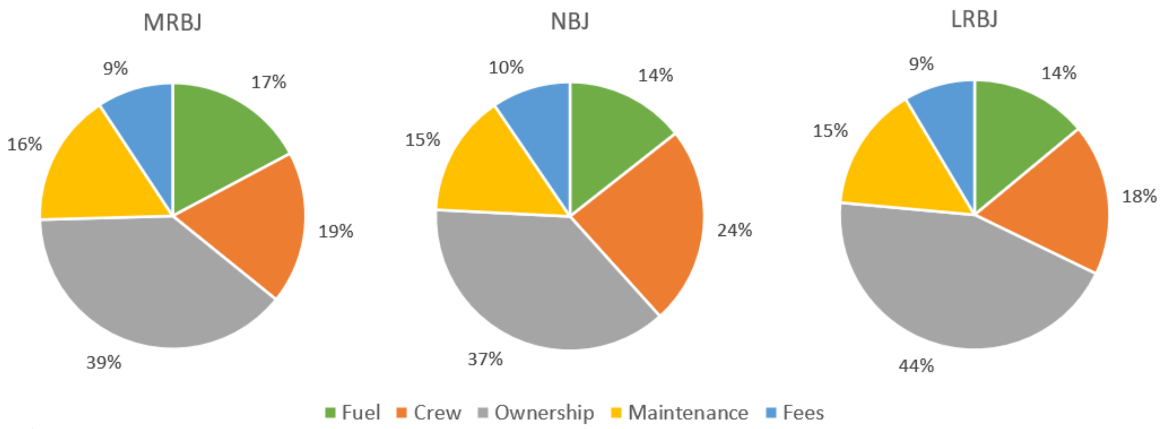


Figure 3.14: Aircraft DOC comparison.

As visible, the NBJ and MRBJ cost are similar since there is no significant variation in the MTOW, whereas the LRBJ presents higher results, particularly for the Capital and Maintenance costs. These results are easy to guess, as the various Direct Cost items depend highly on the aircraft's weight.

The Operational Expenses and the baseline Ticket Price comparison are visible in Table 3.22 below. There is an evident difference in the baseline Ticket Price, where the value achieved through the NBJ is the lowest; however, the design mission considered is not unique for the three aircraft, thus a possible discussion at this moment is meanless. A more in-deep analysis related to this aspect is discussed the Section 3.3, where the aircraft is compared on the same route, allowing more reliable conclusions to be drawn.

	MRBJ	NBJ	LRBJ
$OPEX_{year}$ [€]	6 838 200	7 752 300	9 126 500
$OPEX_{flight}$ [€]	19 895	29 179	39 098
$OPEX_{hour}$ [€]	1 911	2 143	2 511
$P_{tkt_{base}}$ [€]	3 247	4 666	5 009

Table 3.22: Aircraft OPEX comparison.

3.3. Scenario analysis

The evaluation of the economic performance of an aircraft is a vital aspect, especially when a new solution is proposed on the market. Referring to the NBJ in particular, its evaluation in the operational field can be a critical aspect. It is therefore essential that this aeroplane is not so disadvantageous compared to its competitors, especially in an industry, that of BJs, where the segmentation between the various aircraft is strongly marked. Notwithstanding, NBJ can represent a considerable advantage for those who desire to achieve higher performance when required, while saving money compared to a traditional long-haul BJ.

In order to evaluate the NBJ, various scenarios are defined in the following paragraphs, in which the NBJ is carefully evaluated to its competitors, i.e. the MRBJ and LRBJ, and conclusions are drawn on what has been achieved. In addition, an analysis on the average aircraft utilisation during the year is conducted, based on which routes are travelled most, and finally, an analysis on the change in ticket price based on how many passengers are carried annually on average.

3.3.1. Scenario definition

This paragraph presents the various scenarios, i.e. different flights, on which the NBJ, MRBJ and LRBJ are tested, evaluated and finally commented on. The definition of possible flight arises in identifying four possible general route categories: short-range (SR), medium-range (MR), long-range (LR) and ultra long-range (ULR). These four general routes are analysed and then, thanks to the data provided in the EBAA Yearbook [24], they are contextualised by finding actual routes that can be identified within each category. In other words, four actual flights are now presented, of which the first three are routes frequented by BJs on the European continent. The routes chosen are in Table 3.23.

Category	Flight	Distance
Short-Range	Milan (IT) - London (GB)	959 km
Medium-Range	Istanbul (TR) - Doha (QA)	2 692 km
Long-Range	London (GB) - New York (US)	5 554 km
Ultra Long-Range	Milan (IT) - Buenos Aires (BR)	11 172 km

Table 3.23: Scenarios definition (primary).

These hypothetical flights enable to have reference routes, where, thanks to the chosen DOC calculation method, it is possible to derive their associated operating cost.

Two extra scenarios are added to these four for the explained reasons. The MRBJ cannot perform the Ultra Long-Range route because it is beyond its design performance, so an additional Short-Range flight is added to the existing one. In the case of the LRBJ, a Long-Range route is added to ensure a more extensive and detailed comparison with the NBJ. The flight are in Table 3.24 below.

Category	Flight	Distance
Short-Range	Milan (IT) - Rome (IT)	470 km
Long-Range	Buenos Aires (BR) - Mexico City (MX)	7 377 km

Table 3.24: Scenarios definition (secondary).

The short-range one is executed only by the NBJ and MRBJ, as aircraft in the LRBJ category can seldom perform similar flights. On the other hand, the Long-Range further route is flight only by the LRBJ and NBJ, again because the range requested is outside the performance of the MRBJ.

The results from the illustrated scenarios are obtained using Hyperion's 'Mission Simulation' function. This feature allows to deploy a sized aircraft on a defined mission within the aircraft's capabilities. The mission is defined with a payload, range, number of pilots and initial tank level which may differ from the design point of the aircraft. In fact, in order to stay within the maximum number of flight hours that a pilot may perform continuously, a third pilot is considered for each route over 5 500 km, switching over from one of the two initial pilots during the flight. Lastly, the amount of loaded fuel required to execute the flight is increased by 2.5 % for safety reasons and to ensure that the tank at the end of the mission is not entirely emptied.
The number of embarked passengers and crew for each mission is shown in Table 3.25.

Flight	N_{pax}	N_{pil}	N_{fa}
Milan - Rome	6	2	1
Milan - London	6	2	1
Istanbul - Doha	5	2	1
London - New York	4	3	1
Buenos Aires - Mexico City	4	3	1
Milan - Buenos Aires	3	3	1

Table 3.25: Number of passengers and crew members for scenarios.

3.3.2. Route and utilisation analysis

The annual utilisation of an aircraft, in terms of hours flown and average distance travelled, is crucial in determining its approximate operating costs. Indeed, a business jet is generally used more for routes far below its real capacity, i.e. range.
A practical example would be the Dassault Falcon 2000, an aircraft that provides a range of up to 7 400 km carrying 6 passengers but which, according to data provided by EBAA, has an average distance flown of only 1 046 km and an average flight time of about 1hr 35m. This argument can be made for all aircraft, including Long-Range BJs; in fact, an aircraft such as the Dassault Falcon 8X has an average distance flown of only 1 919 km.

Several considerations can be drawn from this data; it is evident that short-haul routes are the preferred ones in every BJs category, so it is essential that an aircraft can perform the most significant number of short-haul flights and long-haul, when required. Features such as flexibility and adaptability to every situation are fundamental, along with maximum passenger comfort, a key element for this sector.

To better understand the situation, Table 3.26 presents data from six BJs usually operating in the European Union; it includes both MidSize and Long-Range aircraft, showing their distances flew and average flight times. Table 3.27, on the other hand, shows the division between domestic, intra-European and extra-European flights. The planes are arranged in ascending order of MTOW and their nominal range is shown.

Model	MTOW [kg]	R [km]	Average Distance [km]	Average Time
Falcon 2000	19 414	7 408	1 046	1h 35m
Challenger 600	21 863	7 408	1 577	2h 25m
Legacy 600	24 300	7 223	1 628	2h 27m
Falcon 7X	31 751	11 019	1 730	2h 33m
Global 5000	41 957	11 556	2 343	3h 20m
Gulfstream G650	47 000	12 964	2 578	3h 31m

Table 3.26: Average distance and time flight of BJs (source: EBAA).

Model	Intra Europe [%]	Domestic [%]	Extra Europe [%]
Falcon 2000	63.9	31.7	4.4
Challenger 600	67.2	19.5	13.3
Legacy 600	75.3	14.5	10.1
Falcon 7X	62.2	26.4	11.4
Global 5000	64.8	15.8	19.4
Gulfstream G650	59.8	19.8	20.4

Table 3.27: Geographical division of flights (source: EBAA).

It is immediately perceptible that there is a clear difference between the nominal range and average distance flown. This reinforces the idea that most flights are short- or medium-haul. In addition, the percentage of flights presented in Table 3.27 also agrees with the considerations made: most are intra-European flights, of which a significant proportion are domestic (i.e. the flight is operated entirely within one country), meaning that the flight distance is not considerably high.

Based on the data and considerations outlined above, the average annual utilisation of the three aircraft under consideration, i.e. the NBJ, MRBJ and LRBJ, is now proposed. Three different types of aircraft annual utilisation are proposed: Short-Range utilisation (SRu), Medium-Range utilisation (MRu) and Long-Range (LRu) utilisation. In the case of the SRu, short-range flights predominate over the others, and so does the analogue for the other two utilisations. The number of SR, MR, LR and ULR flights utilised are different for the three aircraft tested because of a fixed amount of hours flown per year; this is because in the MRBJ, short-haul flights predominate, and conversely, the long-haul flights for the LRBJ. Naturally, in the case of the MRBJ, there are no ULR flights as they exceed its nominal performance.

The first step to conceive an annual utilisation of the aircraft is to assume how the aircraft is used annually in a percentage approach, divided into the four corresponding flights, i.e. short-, medium-, long- and ultra-long-range flights. The flight percentages are hypotheses based on data from EBAA and from Sirio S.p.A. as a result of an interview with them. To sum up, the percentage used are shown in Table 3.28 for the MRBJ, Table 3.29 for the NBJ and Table 3.30 for the LRBJ.

Flight	**SRu**	**MRu**	**LRu**
Short Range	60 %	55 %	50 %
Medium Range	35 %	35 %	35 %
Long Range	5 %	10 %	15 %

Table 3.28: Utilisation data for MRBJ.

Flight	**SRu**	**MRu**	**LRu**
Short Range	60 %	55 %	50 %
Medium Range	35 %	30 %	25 %
Long Range	5 %	10 %	15 %
Ultra Long Range	0 %	5 %	10 %

Table 3.29: Utilisation data for NBJ.

Flight	**SRu**	**MRu**	**LRu**
Short Range	25 %	20 %	15 %
Medium Range	45 %	40 %	35 %
Long Range	25 %	30 %	35 %
Ultra Long Range	5 %	10 %	15 %

Table 3.30: Utilisation data for LRBJ.

Successively, the percentages shown above are applied to an annual aircraft usage of 500 hours. This value is assumed after the comparison with Sirio S.p.A., as their aircraft usually have an average yearly utilisation around that value. After that, having the flight time information for each scenario, the flight hours corresponding to each percentage are transformed into the corresponding number of flights. The number of these flights for each use is shown in Table 3.31 for the MRBJ, Table 3.32 for the NBJ and Table 3.33 for the LRBJ, along with the average flight time and average flight distance for each aircraft's annual utilisation (i.e. SRu, MRu and LRu). Note that the scenarios used are exclusively those in Table 3.23.

Flight	SRu N_{flight}	MRu N_{flight}	LRu N_{flight}
Short Range	114	104	95
Medium Range	38	38	38
Long Range	3	6	9
Av. $Time_{flight}$	3h 14m	3h 22m	3h 31m
Av. $Dist_{flight}$	1 627 km	1 747 km	1 877 km

Table 3.31: Yearly flight for MRBJ.

Flight	SRu N_{flight}	MRu N_{flight}	LRu N_{flight}
Short Range	114	104	95
Medium Range	38	32	27
Long Range	3	6	9
Ultra Long Range	0	2	3
Av. $Time_{flight}$	3h 14m	3h 27m	3h 42m
Av. $Dist_{flight}$	1 627 km	1 820 km	2 043 km

Table 3.32: Yearly flight for NBJ.

Flight	SRu N_{flight}	MRu N_{flight}	LRu N_{flight}
Short Range	47	38	28
Medium Range	49	43	38
Long Range	16	19	22
Ultra Long Range	2	3	5
Av. $Time_{flight}$	4h 24m	4h 50m	5h 21m
Av. $Dist_{flight}$	2 647 km	3 016 km	3 464 km

Table 3.33: Yearly flight for LRBJ.

The three illustrated tables show that the annual average distance travelled data are comparable with those from EBAA in Table 3.26. On the other hand, the average yearly flight time appears to be higher than the EBAA data. Nevertheless, it is crucial to remember that each flight includes the 150 km diversion manoeuvre, which itself comprises a loiter time of 30 minutes. Hence, the distance and flight time are slightly higher.

This data allows for more detailed information on annual operating costs by actualising the work to hypothetical real utilisations. With this, it is possible to derive the most profitable utilisation and whether the NBJ is competitive.

Another interesting aspect that deserves attention is the average number of passengers transported during the year. As is well known, in the case of commercial airlines, having the aircraft with all seats occupied is the primary objective to be pursued to maximise profits. The same reasoning, however, hardly applies in the world of business jets; indeed, it follows an opposite path. This sector satisfies unique and different demands than the commercial one, thus presenting a different business model. Approaching this area is particularly difficult since it has insufficient public data.

A breakthrough in this work was made possible thanks to an interview with Sirio S.p.A, an Italian company founded in 1984 that works in the Aircraft Management and Maintenance Organisation sector and comprises a fleet of 11 business aircraft based in Milan Linate. It emerged from this meeting that the number of average passengers transported varies according to the route length. In detail, on short- and medium-haul flights, where there are no beds on board, the number of passengers is on average from 2 to 4 persons, while on long-haul flights, the capacity is the same as the number of beds on board, e.g. 10 standard seats are 5 beds, so 4 or 5 passengers are carried. It can be deduced that hardly all available seats are occupied.

In the case of long-haul flights, the average number of passengers is justified, as maximum comfort must be guaranteed on board and in these cases, a simple reclining seat is not sufficient, beds are necessary. On the other hand, regarding short- and medium-haul routes, the data illustrated by Sirio S.p.A. is barely reflected in the commercial world. This is because, generally, a BJ is chartered by a single customer, who, having to move for business reasons, moves in total comfort with his staff. Or, during the day, few people require that route, so the number of passengers is relatively low. Of course, there are situations where more passengers are transported, but as a percentage, they represent a minority.

As a result of the above considerations, three different types of aircraft utilisation scenarios are proposed based on the average annual number of passengers carried for short-haul/medium-haul and long-haul routes. These scenarios reflect three possible cases:

- Low Passengers transported (LPt)

- Normal Passengers transported (NPt)
- High Passenger transported (HPt)

In the first case, a low number of passengers is considered on all routes, i.e. SR, MR, LR and ULR, while in the other two cases the average number tends to increase. The precise data used are shown in Table 3.34 below.

Flight	Pax_{LPt}	Pax_{NPt}	Pax_{HPt}
Short Range	2	4	6
Medium Range	2	4	6
Long Range	3	4	5
Ultra Long Range	3	4	5

Table 3.34: Input for passengers analysis.

With data on the average route distance travelled and the number of passengers, it is possible to obtain several cases in which there is an evident variation in operating costs, particularly in ticket prices.

3.3.3. Results and discussion

This section presents and discusses the results obtained by adopting the numerous scenarios explained in previous sections. First, the operating costs of the three aircraft on the six different routes are shown, highlighting the differences. Secondly, the average annual aircraft utilisation analysis is presented in terms of routes flown and average number of passengers.

Scenarios results

This section aims to show the results obtained through Hyperion's "Mission Simulation" in calculating operating costs, i.e. DOC, on the previously defined routes. Each route is analysed individually, highlighting and explaining possible differences. The flight time indicated, equal for all the three aircraft for simplicity, refers to the flight plus the diversion manoeuvre of 150 km.

Milan - Rome. This route is the most flown in Italy, as it links the two major cities in the country. It has a distance of around 470 km and a flight time of 2h 03m. Due to the short distance, this scenario is only used for the MRBJ and NBJ. The results in Table 3.35

below show that the difference in Operating Expenses and Ticket Price is relatively small, with the latter being slightly higher in the NBJ.

	MRBJ	NBJ
DOC$_{flight}$ [€]	6 643	6 930
OPEX$_{flight}$ [€]	3 356	3 317
OPEX$_{hour}$ [€]	1 428	1 371
P$_{tkt_{base}}$ [€]	664	693

Table 3.35: Milan - Rome scenario results.

Milan - London. This flight is one of the most requested from Italy, as it links Milan with the capital of the United Kingdom, one of Europe's most important business poles. It has a distance of 969 km and a flight time of 2h 38m; thus, the results are presented for all three aircraft in Table 3.36. In this scenario, the MRBJ shows a slightly higher Ticket Price with respect to the NBJ, whereas the LRBJ present significantly higher results. This is expected since the LRBJ is designed to be competitive on longer routes.

	MRBJ	NBJ	LRBJ
DOC$_{flight}$ [€]	8 324	8 567	12 006
OPEX$_{flight}$ [€]	4 383	4 272	5 138
OPEX$_{hour}$ [€]	1 504	1 438	1 682
P$_{tkt_{base}}$ [€]	832	857	858

Table 3.36: Milan - London scenario results.

Istanbul - Doha. The route is taken from data about the Bombardier Global 5000 on the EBAA website. It connects Istanbul with the Qatari capital Doha. The distance is of 2 692 km and the flight time is 4h 38m. The results in Table 3.37 show that there is parity between NBJ and MRBJ, while LRBJ has significantly higher costs.

	MRBJ	NBJ	LRBJ
DOC$_{flight}$ [€]	14 337	14 487	19 935
OPEX$_{flight}$ [€]	8 104	7 744	9 260
OPEX$_{hour}$ [€]	1 645	1 567	1 845
P$_{tkt_{base}}$ [€]	1 436	1 448	1 423

Table 3.37: Istanbul - Doha scenario results.

London - New York. This route is one of the most popular in the West. In fact, EBAA data shows that it is one of the main routes of the Bombardier Global Express 5000/6000 and the Gulfstream G650, all long-haul BJs. It connects two very frequented cities for both tourism and business. The distance is of 5 554 km and the flight time is 7h 55m. The Table 3.38 shows that the NBJ is slightly cheaper than the MRBJ in terms of OPEX per flight and airfare. The LRBJ, on the other hand, always shows higher outcomes.

	MRBJ	NBJ	LRBJ
$\mathbf{DOC_{flight}}$ **[€]**	26 839	26 596	35 576
$\mathbf{OPEX_{flight}}$ **[€]**	16 753	15 826	18 519
$\mathbf{OPEX_{hour}}$ **[€]**	2 033	1 929	2 226
$\mathbf{P_{tkt_{base}}}$ **[€]**	2 684	2 661	2 539

Table 3.38: London - New York scenario results.

Buenos Aires - Mexico City. This route, along with the next, is not reflected in the EBAA data but is conceived for the purpose of having additional scenarios to compare aircraft. It has a distance of 7 377 km and a flight time of 10h 02m, linking the capital of Mexico with Buenos Aires, Brazil. For this scenario, only the NBJ and LRBJ are presented. The results in Table 3.39 point out how the NBJ represents a valid alternative to the LRBJ, as it is cheap and it offers the same performances.

	NBJ	LRBJ
$\mathbf{DOC_{flight}}$ **[€]**	33 831	45 006
$\mathbf{OPEX_{flight}}$ **[€]**	20 517	23 946
$\mathbf{OPEX_{hour}}$ **[€]**	1 993	2 302
$\mathbf{P_{tkt_{base}}}$ **[€]**	3 388	3 215

Table 3.39: Buenos Aires - Mexico City scenario results.

Milan - Buenos Aires. As stated above, this route is created to have a test bench on ultra long-range routes. The distance of 11 172 km is considerable and there are currently very few airlines offering direct non-stop flights with a travel time of more than 15 hours. The flight time is 14h 25m Even in this scenario, it can be seen that the NBJ has lower costs than the LRBJ; the 'baseline' Ticket Price is, in fact, more than 20 % lower. Results are shown below in Table 3.40.

	NBJ	LRBJ
DOC_{flight} [€]	50 170	65 874
$OPEX_{flight}$ [€]	31 395	36 330
$OPEX_{hour}$ [€]	2 136	2 452
$P_{tkt_{base}}$ [€]	5 022	4 709

Table 3.40: Milan - Buenos Aires scenario results.

Before concluding the paragraph about the scenario results, a graphical representation of the Direct Cost per flight variation, for the six routes presented, is shown in Figure 3.15, along a similar graph but related to the Operational Expenses per flight in Figure 3.16.

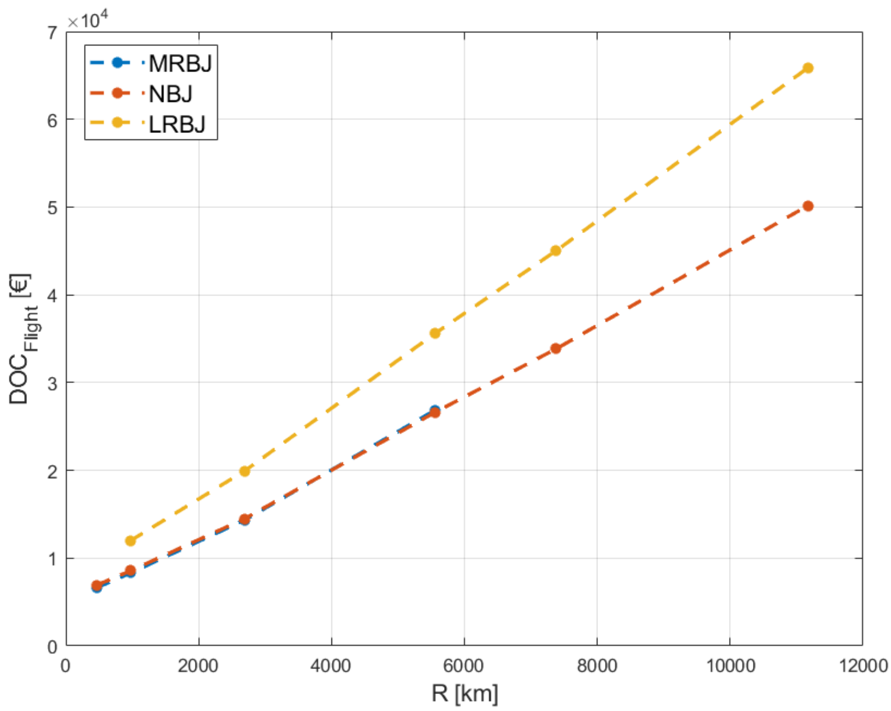


Figure 3.15: Variation of DOC_{flight}.

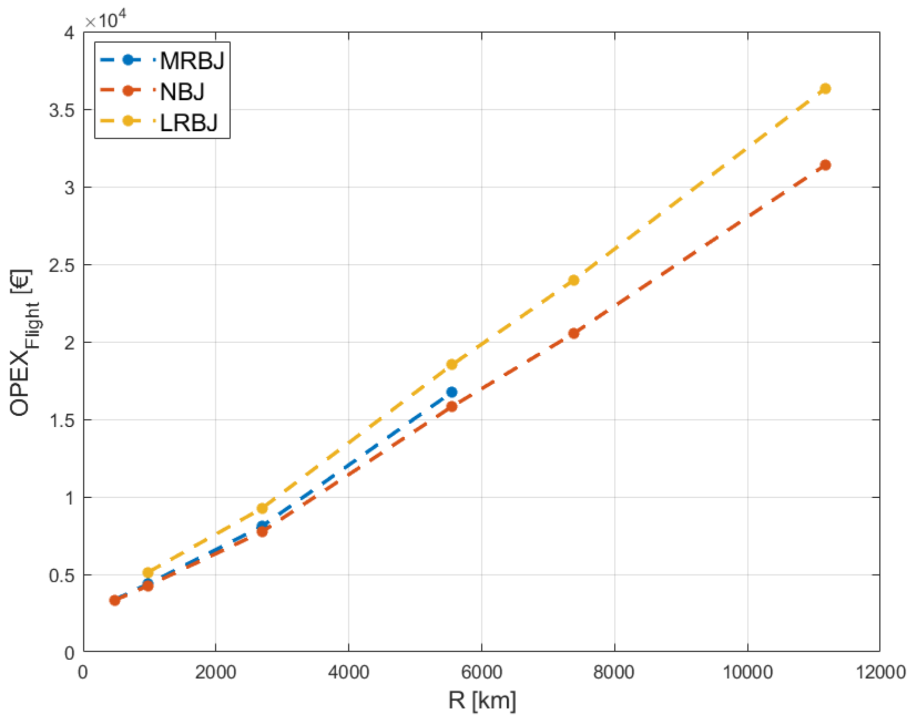


Figure 3.16: Variation of $OPEX_{flight}$.

It can be clearly observed that the cost trend is very similar between the MRBJ and the NBJ, where the $OPEX_{flight}$ of the MRBJ are always slightly higher than those of the NBJ. Finally, the LBJ's costs are always higher than those of the other two aircraft due to its higher running costs.

Utilisation analysis results

The purpose of this section is to provide an overview of the results obtained from the considerations made above, in terms of an analysis of average annual aircraft utilisation, from the point of view of the distance travelled and the number of passengers carried.

With regard to the analysis of aircraft utilisation in terms of the number of SR, MR, LR and ULR flights during the year, results are shown for the three aircraft, divided into the three different types of use: short-range, medium-range and long-range.

Short-Range utilisation. From Table 3.41 below, the annual and per-flight costs of the MRBJ and NBJ are very similar. In detail, the NBJ has lower operating costs per flight and time than the MRBJ, considering an annual utilisation where short-haul flights are predominant. On the other hand, DOCs per year and per flight are slightly higher due to the higher capital cost in the NBJ. Finally, on short-haul utilisation, the LRBJ has significantly disadvantageous costs than the other two aircraft.

	MRBJ	NBJ	LRBJ
$\mathbf{DOC_{year}}$ [€]	1 575 697	1 607 146	2 219 148
$\mathbf{OPEX_{year}}$ [€]	858 357	829 150	1 048 974
$\mathbf{DOC_{flight}}$ [€]	10 176	10 379	19 543
$\mathbf{OPEX_{flight}}$ [€]	5 543	5 354	9 238
$\mathbf{OPEX_{hour}}$ [€]	1 717	1 658	2 098
$\mathbf{P_{tkt_{base}}}$ [€]	1 017	1 038	1 392

Table 3.41: SRu results comparison.

Medium-Range utilisation. Regarding the annual aircraft utilisation where there is a higher presence of medium-haul flights, it can be observed in Table 3.42 that the results are very similar to those obtained with a Short-Range utilisation. It therefore follows that the NBJ is slightly more advantageous than the MRBJ in terms of operating costs. Again, the LRBJ has higher operating costs.

	MRBJ	NBJ	LRBJ
$\mathbf{DOC_{year}}$ [€]	1 581 426	1 618 633	2 229 388
$\mathbf{OPEX_{year}}$ [€]	869 651	851 227	1 071 712
$\mathbf{DOC_{flight}}$ [€]	10 648	11 174	21 528
$\mathbf{OPEX_{flight}}$ [€]	5 856	5 876	10 349
$\mathbf{OPEX_{hour}}$ [€]	1 814	1 702	2 350
$\mathbf{P_{tkt_{base}}}$ [€]	1 064	1 118	1 530

Table 3.42: MRu results comparison.

Long-Range utilisation. In reference to the annual utilisation of the aircraft with the greatest number of long-haul flights, thanks to Table 3.43, it can be seen that in this case, the MRBJ has lower operating costs per flight than the NBJ, although the difference, in general, is quite negligible. Even in this usage scenario, LRBJ shows higher costs, mainly due to higher capital and running costs.

	MRBJ	**NBJ**	**LRBJ**
DOC_{year} [€]	1 587 156	1 630 121	2 239 627
$OPEX_{year}$ [€]	880 944	873 305	1 094 451
DOC_{flight} [€]	11 163	12 088	23 938
$OPEX_{flight}$ [€]	6 196	6 476	11 698
$OPEX_{hour}$ [€]	1 919	1 747	2 657
$P_{tkt_{base}}$ [€]	1 116	1 209	1 697

Table 3.43: LRu results comparison.

NBJ Utilisation analysis. Another investigation that can be carried out is to analyse how the aircraft's operating costs may change according to its annual utilisation, i.e. SRu, MRu and LRu. Thus, Table 3.44 shows the three different utilisations for the NBJ, comparing both costs and the value of the 'baseline' airline ticket.

	SRu	**MRu**	**LRu**
DOC_{year} [€]	1 607 146	1 618 633	1 630 121
$OPEX_{year}$ [€]	829 150	851 227	873 305
DOC_{flight} [€]	10 379	11 174	12 088
$OPEX_{flight}$ [€]	5 354	5 876	6 476
$OPEX_{hour}$ [€]	1 658	1 702	1 747
$P_{tkt_{base}}$ [€]	1 038	1 118	1 209

Table 3.44: NBJ Utilisation analysis results.

It can be deduced that as annual long-haul flights increase, annual and per-flight operating expenses increase. This is mainly due to higher fuel consumption, higher airport taxes (higher aircraft weight as there is more fuel for the flight), and higher crew expenses (need to have a third pilot on board for some flights). Expenses due to maintenance and capital remain about the same. Despite this increase, the difference between uses is not so marked, indicating that the aircraft, if used at long range, does not have major economic disadvantages compared to a more short-range use.

Analysis on the number of passengers carried The second investigation concerns the average number of passengers carried on each route, i.e. SR, MR, LR and ULR flights. As seen above, the number of passengers is significantly different from the numbers on board a typical airliner, understood as the number of passengers transported compared to the actual capacity of the aircraft, which is why the same considerations cannot be made as in the commercial sector; in other words, the more passengers transported, the greater the profit and recovery of operating expenses.

However, the Business Jet sector is quite arduous to analyse, given its uniqueness in economic terms. Definitely, to obtain more reliable data, it would be helpful to know more about the market dynamics of the various Air Charter/Air Taxi companies in order to understand how each company can recoup its expenses and make profit.

Nonetheless, the results of the analysis of operating costs variation based on the number of passengers transported are herein presented. The four routes used are the ones presented in Table 3.23. The principal idea is to show the variation of DOC_{flight}, $OPEX_{flight}$, $P_{tkt_{base}}$ and P_{tkt} as the number of passengers changes. The last term just cited, P_{tkt}, refers to a hypothetical ticket price to cover all operational expenses incurred. It follows that the more passengers are carried on a flight, the lower this value is. In other words, it is the result of dividing DOC_{flight} by the number of passengers on board and not by the number of seats available, which is the definition of $P_{tkt_{base}}$.

Before commenting on the results, one can expect the variation in operating costs per flight and per hour to be relatively low, as the variation in fuel as passenger numbers change is minimal, as well as the variation in airport taxes. Therefore, the four tables below present the operating cost variation for the selected routes.

	LPt	**NPh**	**HPt**
DOC_{flight} [€]	8 187	8 503	8 820
$OPEX_{flight}$ [€]	3 864	4 207	4 457
$P_{tkt_{base}}$ [€]	819	850	882
P_{tkt} [€]	4 219	2 126	1 428

Table 3.45: Short-Range flight: analysis on transported passengers.

	LPt	**NPh**	**HPt**
DOC_{flight} [€]	14 117	14 449	14 776
$OPEX_{flight}$ [€]	7 378	7 708	8 035
$P_{tkt_{base}}$ [€]	1 412	1 445	1 478
P_{tkt} [€]	7 184	3 612	2 421

Table 3.46: Medium-Range flight: analysis on transported passengers.

	LPt	NPh	HPt
DOC_{flight} [€]	26 283	26 597	27 116
$OPEX_{flight}$ [€]	15 508	15 821	16 118
$P_{tkt_{base}}$ [€]	2 628	2 660	2 693
P_{tkt} [€]	8 845	6 649	5 173

Table 3.47: Long-Range flight: analysis on transported passengers.

	LPt	NPh	HPt
DOC_{flight} [€]	49 920	50 198	50 489
$OPEX_{flight}$ [€]	31 116	31 394	31 187
$P_{tkt_{base}}$ [€]	4 992	5 020	5 049
P_{tkt} [€]	16 723	12 550	10 048

Table 3.48: Ultra Long-Range flight: analysis on transported passengers.

As can be deduced from the above results, in all four flights shown, operating costs show the same trend; they tend to rise slightly as the number of passengers carried per flight increases. In detail, referring, for example, to the $OPEX_{flight}$ value, there is a more marked relative difference in short-haul and medium-haul flights, ranging from 5 to 8 %, while in long-haul flights, the relative variation is much lower and negligible. The reason why this variation varies from flight to flight is due to the different fuel consumption: in short-haul flights, carrying more or fewer passengers can have a more marked influence on the total consumption, from a relative point of view, whereas in long-haul flights the difference in consumption due to a different number of passengers is slight when compared to the total fuel consumption to accomplish the flight.

Lastly, the change in airfare deserves attention. The $P_{tkt_{base}}$ value follows the same trend as operating costs, i.e. it increases as the number of passengers increases, while P_{tkt} follows an opposite trend and is enormously different from the other ticket value.
In this analysis, the value of P_{tkt} is only calculated to show what the difference with $P_{tkt_{base}}$ might be. Both values are purely indicative; however, their difference highlights how the ticket cost management policy is crucial to its achievement; on the one hand, we have a ticket cost that does not cover all operational expenses incurred for that flight (unless flying at maximum capacity), on the other hand, we have a ticket value that, given a certain number of passengers, covers all operational expenses.

To conclude, to accurately estimate the cost of an airline ticket, it is vital to know the business dynamics of a company operating in the sector.

Discussion of the results

This last paragraph aims to discuss in more profound detail the results obtained from the analysis of average aircraft yearly utilisation and the number of passengers transported per route.

Regarding the annual use of the aircraft, the results show that in most cases, the NBJ is a worthwhile solution compared to both the MRBJ and the LRBJ, the latter of which, supporting evidence, is the more economically disadvantageous choice. However, it is essential to provide some clarification.

The difference between MRBJ and NBJ is not so marked, in terms of both weight and flight performance. The latter, except for the nominal range, remain unchanged between the two aircraft, while from the point of view of weight and size, there are more obvious differences. The NBJ represents an innovative solution, incorporating hypothetical future developments in both aerodynamics and propulsion, enabling it to perform the same missions as the MRBJ more efficiently. However, the NBJ is actually a bulkier aircraft, both in terms of weight and size (e.g. fuselage length and wingspan) and this could represent an operational limitation for the aircraft (e.g. inability to operate at small airports). It follows that the MRBJ also has its strengths.

Regarding the difference between NBJ and LRBJ, following the data shown, it appears that LRJ is always a disadvantageous choice compared to NBJ. Even here, it is crucial to clarify a few aspects. The LRBJ is a jet dedicated to long-haul flights and brings specific characteristics peculiar to its category; it is a heavier and bulkier aircraft, but thanks to its larger size, it provides even more comfort inside the cabin, offering more seats and better flight performance than the NBJ. On the other hand, the latter being closer in size to a MidSize category cannot provide the same level of comfort and performance as a long-haul aircraft. However, the NBJ may be a worthwhile alternative for those who generally use aircraft for short-haul but do not want to deprive themselves of long-haul flights. The latter idea is also reinforced by the EBAA data in Table 3.26, where it is noted that aircraft such as the Dassault Falcon 7X (long-haul aircraft) are mainly used for short distances, thus not representing a cost-effective option. The NBJ could therefore represent a more flexible and economical solution than a long-haul BJ.

In conclusion, the three aircraft presented in the analyses have their merits and demerits, and definitely, an investigation of their average utilisation is crucial to understand when a solution is cost-effective.

Conclusion

The work carried out in this thesis illustrates how a cost-effective solution can be achieved by proposing an aircraft that lies between two distinct categories of business jets. In detail, the following consideration may be highlighted:

- **Business Jets Market:** The sector is highly segmented, both in terms of aircraft size and the type of propulsion installed, i.e. jets or turboprops. Significant manufacturers, such as Textron Aviation, Bombardier and Dassault Aviation, dominate the BJs production industry. In Europe, air traffic has grown substantially after the Covid-19 pandemic lockdown, although there has been a slight decline recently due to recent geopolitical developments in Europe (consequent to the war in Ukraine). Countries such as France, Germany and the UK turn out to be the busiest and where most of the fleet is concentrated. The BJs' main activities focus on Air Taxi and Air Charter services, mainly operated by private companies. Moreover, most flights are short- to medium-haul, mainly connecting crucial business hubs such as Geneva, London or Paris.

- **BJ Preliminary Sizing:** Satisfactory results can be achieved by making targeted modifications to existing jetliner preliminary sizing methodologies to correctly identify the aircraft category, which differs significantly from airliners.

- **BJ Sensitivity Analysis:** The sensitivity analysis on some crucial flight parameters shows how achieving concrete improvements that lead the aircraft to reduce fuel consumption and emissions is possible. It is deduced how possible future aerodynamics, propulsion and structure developments can positively impact aircraft performance.

- **Conceptual Design of a MidSize BJ Long-Range:** The last part of the thesis, which focused on conceptual design, shows how obtaining a feasible and concrete solution from an initial guess is possible by assuming possible future technical developments in the aerodynamic and propulsion fields. The proposed design solution, i.e. the NBJ, presents weight and performance values comparable with aeroplanes in its class but with numerous advantages in terms of performance, particularly concerning the nominal range.

- **Cost Analysis:** The proposed NBJ, evaluated using cost models that are considered to be a standard in the aviation world, shows no significant increase in operating costs despite its unique features. Comparison with those of a short-range aircraft (MRBJ) and a long-range aircraft (LRBJ) in realistic scenarios, pointed out that the NBJ has numerous economic benefits and can represent a valid alternative to the other two aircraft. The last crucial part of the work, which focused on the average annual utilisation of the aeroplane, reveals how the NBJ represents the best option for those who require a MidSize BJ but desire performance outside its category, an option that was directly suggested to the author by a large BJ operator. In conclusion, the results obtained highlight how a more in-depth and detailed analysis of the costs and utilisation of the aeroplane would better frame the new aircraft, given and considering that the BJs sector focuses on a few key aspects such as quickness in reaching a destination, flexibility of the solution and especially comfort on board.

Future developments

Notwithstanding the results, which are validated and contextualised through scenarios, several open points remain and possible future developments that would make this conceptual design even more concrete and competitive. Specifically, these points are:

- **Aircraft improvements in-depth analysis:** A more detailed analysis of how to apply propulsive and especially aerodynamic improvements would be helpful. Various hints can be found about the use of innovative and more efficient engines, while in the aerodynamic field, more effort must certainly be concentrated on understanding how and where to implement possible upgrades. In addition, the NBJ turns out to be a bulkier aircraft than a traditional MidSize aircraft; it would undoubtedly be helpful to analyse how much this increase in size could impact the flexibility of the solution, as the aircraft could perhaps be unusable at several airports despite a traditional BJ MidSize.

- **Aircraft annual utilisation:** It would be helpful to have more information on the actual annual utilisation of the aircraft in terms of average distance flown, average flight time, the average number of passengers carried, and so on. The collaboration with Sirio S.p.A. was fundamental to the work, and surely more data sharing can be a turning point for a possible future development for the NBJ. Understanding and analysing this sector in more detail is crucial, as it is entirely different from the airliner sector, to understand the immediate needs of BJ company and its clients.

- **Business Jet emission:** It would be worthwhile to understand how to address this issue for business jets, as it is not on the same wavelength as the commercial sector, since it is a period where the fight to reduce emissions is a key building block for the future; there is definitely a need for a game changer in the industry, it is just a question of how and when.

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A | Appendix

Model	Mass [kg]	BPR	Thrust [kN]
Williams FJ33-4	136	3.4	5.3
PW615F	140	140	6.0
PW617F	170	2.7	7.2
Williams FJ44-1AP	209	2.6	8.7
GE Honda HF120	211	2.9	9.1
Williams FJ44-3	239	2.2	12.5
PW530	275	4	12.8
PW535A	317	2.6	15.0
TFE731-2-2B	337	2.7	15.6
PW545A	370	4.1	16.8
TFE731-40	373	2.4	18.2
PW545C	377	3.8	18.3
TFE731-20BR	406	3.1	15.6
TFE731-5BR	408	3.5	21.1
TFE731-60	448	3.9	22.2
PW305A	450	4.3	20.8
PW306A	473	4.5	26.8
PW306C	473	4.5	25.3
HTF7500E	618.7	4.2	31.3
HTF7000	619	4.4	30.4
PW308A	622.3	4.1	29.3
PW308C	623.5	4.1	31.2
AE3007A1	719	5.3	33.7
AE3007C1	720	5.3	30.1
AE3007A1E	730	5.3	36.1
CF34-3A1	751	6.3	41.0
CF34-3B	757	6.3	41.0
AE3007A2	762.5	5.3	42.0
Tay RB183-3	1 339	3.0	61.6
PW814GA	1 408	5.5	68.6
BR710C4-11	1 597	4.2	65.6
BR710	1 597	4	66.0
BR700-725A1-12	1 635.2	4.1	75.2
BR700-710D5-21	1 828.8	4.8	67.8

Table A.1: Complete engine data used for regression.

A/C 1: MTOW = 23 523 kg

Pax	Payload [kg]	Crew [kg]	R [km]
5	675	340	11 432
4	540	340	11 646
3	405	340	11 745
2	270	340	11 783

Table A.2: A/C 1: Range values at a specific number of passengers.

A/C 2: MTOW = 23 310 kg

Pax	Payload [kg]	Crew [kg]	R [km]
5	675	340	11 339
4	540	340	11 546
3	405	340	11 637
2	270	340	11 676

Table A.3: A/C 2: Range values at a specific number of passengers.

A/C 3: MTOW = 23 070 kg

Pax	Payload [kg]	Crew [kg]	R [km]
5	675	340	11 252
4	540	340	11 445
3	405	340	11 516
2	270	340	11 517

Table A.4: A/C 3: Range values at a specific number of passengers.

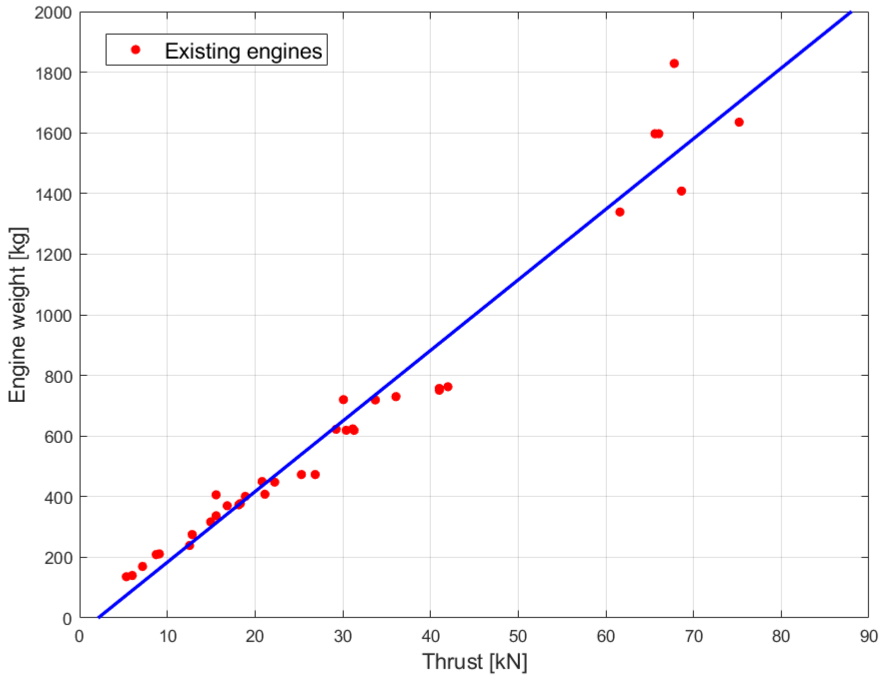
A/C 1: MTOW = 22 865 kg

Pax	Payload [kg]	Crew [kg]	R [km]
5	675	340	11 159
4	540	340	11 355
3	405	340	11 413
2	270	340	11 451

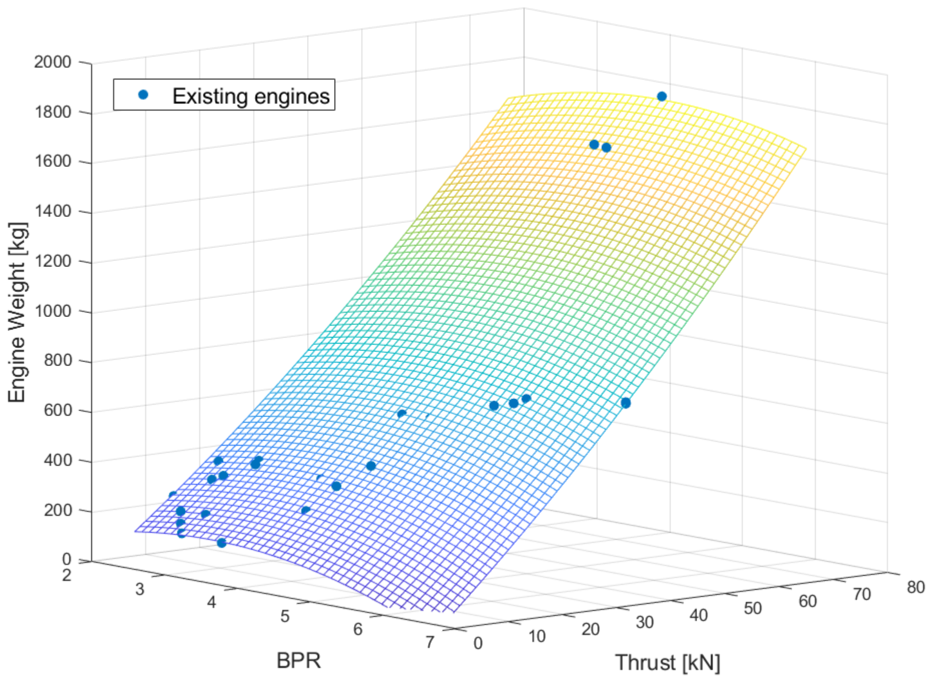
Table A.5: A/C 4: Range values at a specific number of passengers.

	Falcon 8X	LRBJ	Error [%]
MTOW [kg]	33 113	32 869	- 0.7
Empty [kg]	18 597	18 004	- 3.2
Airframe [kg]	16 944	16 421	- 3.1
PL + CW [kg]	1 420	1 420	+ 0.0
Engines [kg]	1 653	1 583	- 4.2
Fuel [kg]	13 096	13 445	+ 2.7
S [m^2]	70.7	87.7	+ 24.1
b [m]	26.3	29.2	+ 11.1
T_{max} [kN]	89.7	87.8	- 2.1

Table A.6: Comparison between Dassault Falcon 8X and LRBJ.



(a) Linear regression.



(b) Multiple quadratic regression.

Figure A.1: Engine historical regression.

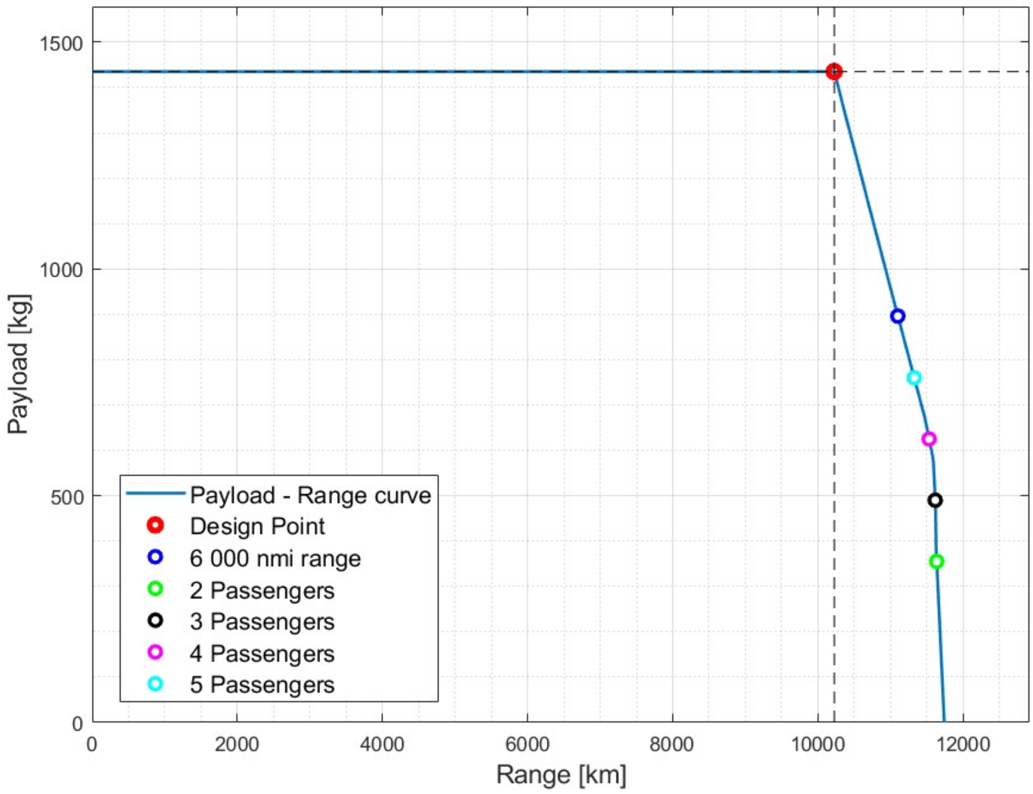


Figure A.2: Payload-Range graph of NBJ with fuselage modified.

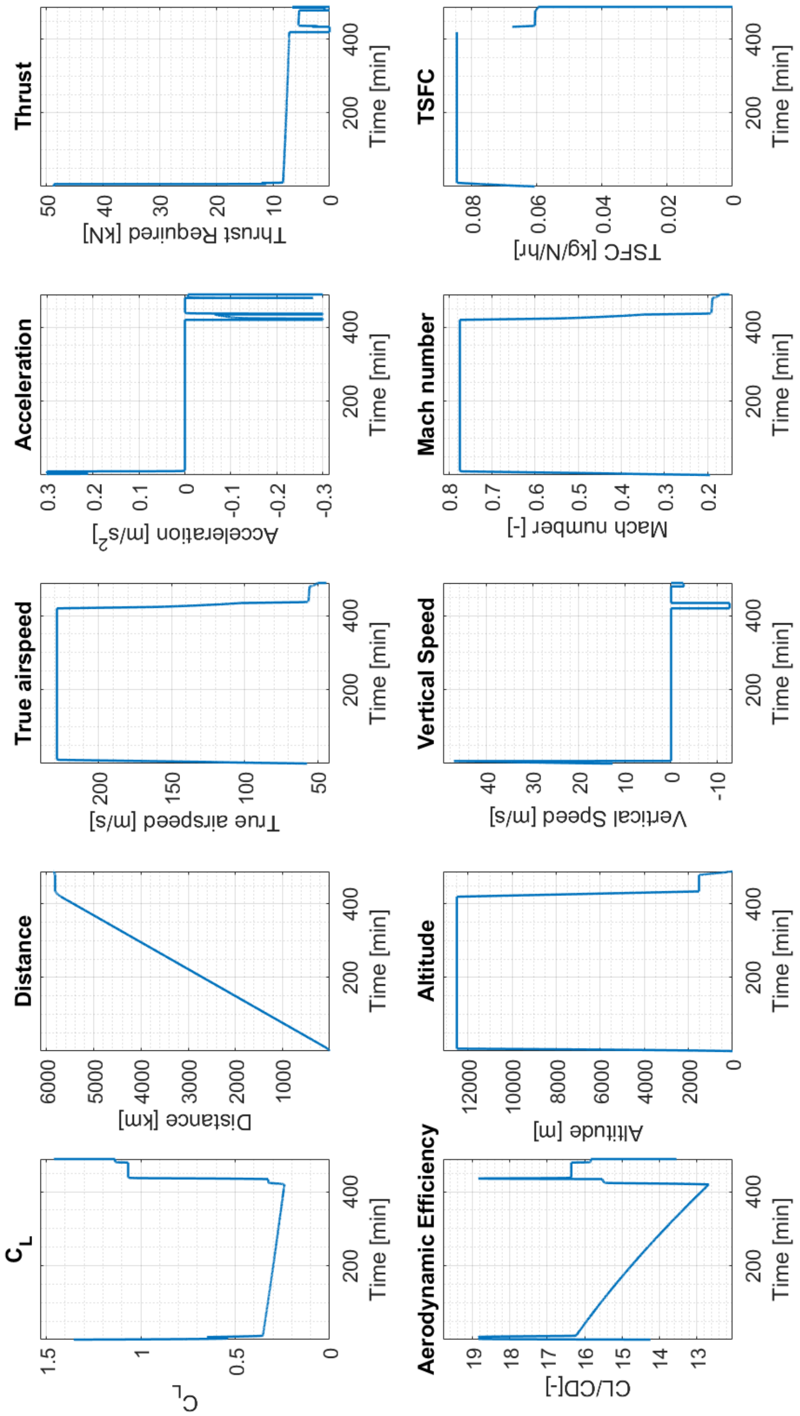


Figure A.3: Cessna Sovereign Flight parameters.

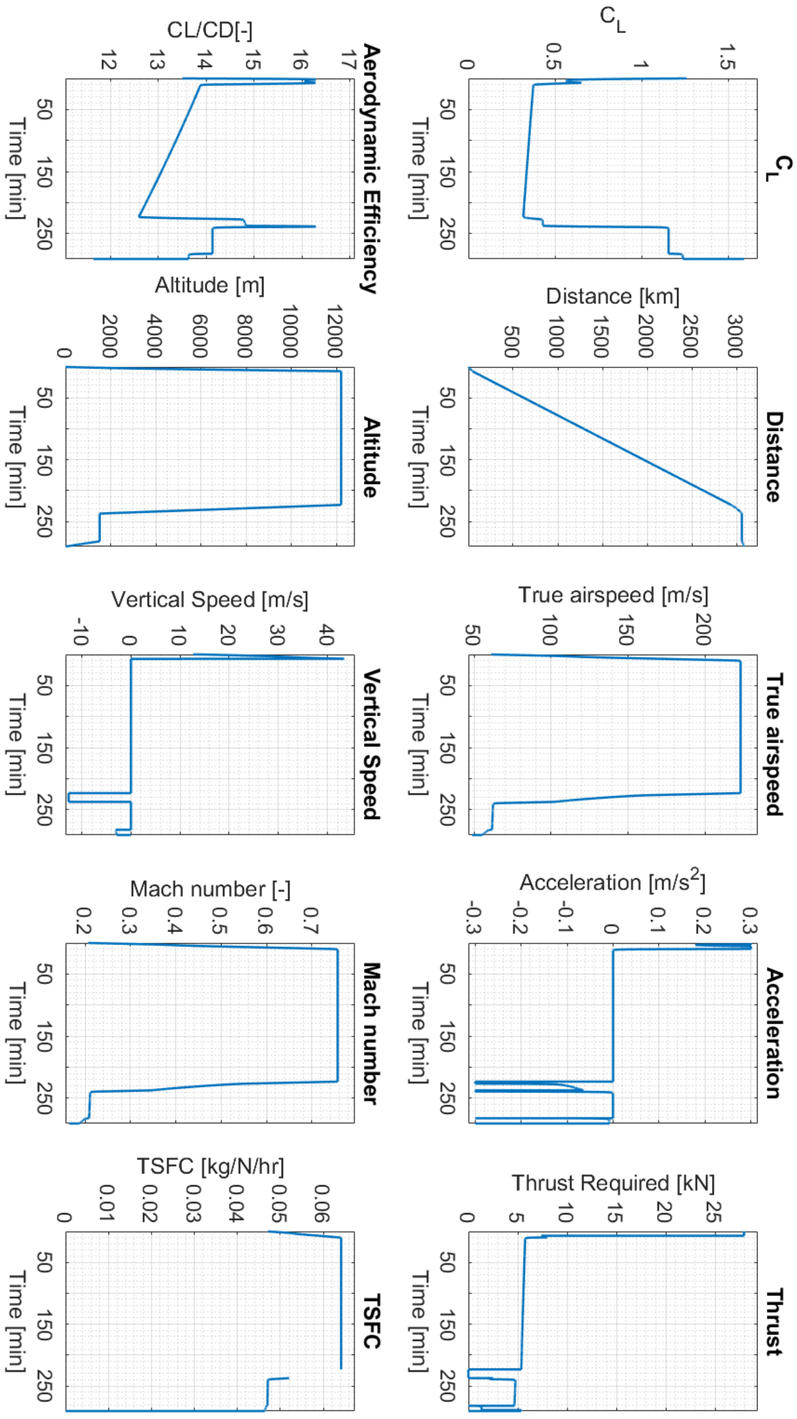


Figure A.4: Embraer Phenom 300E Flight parameters.

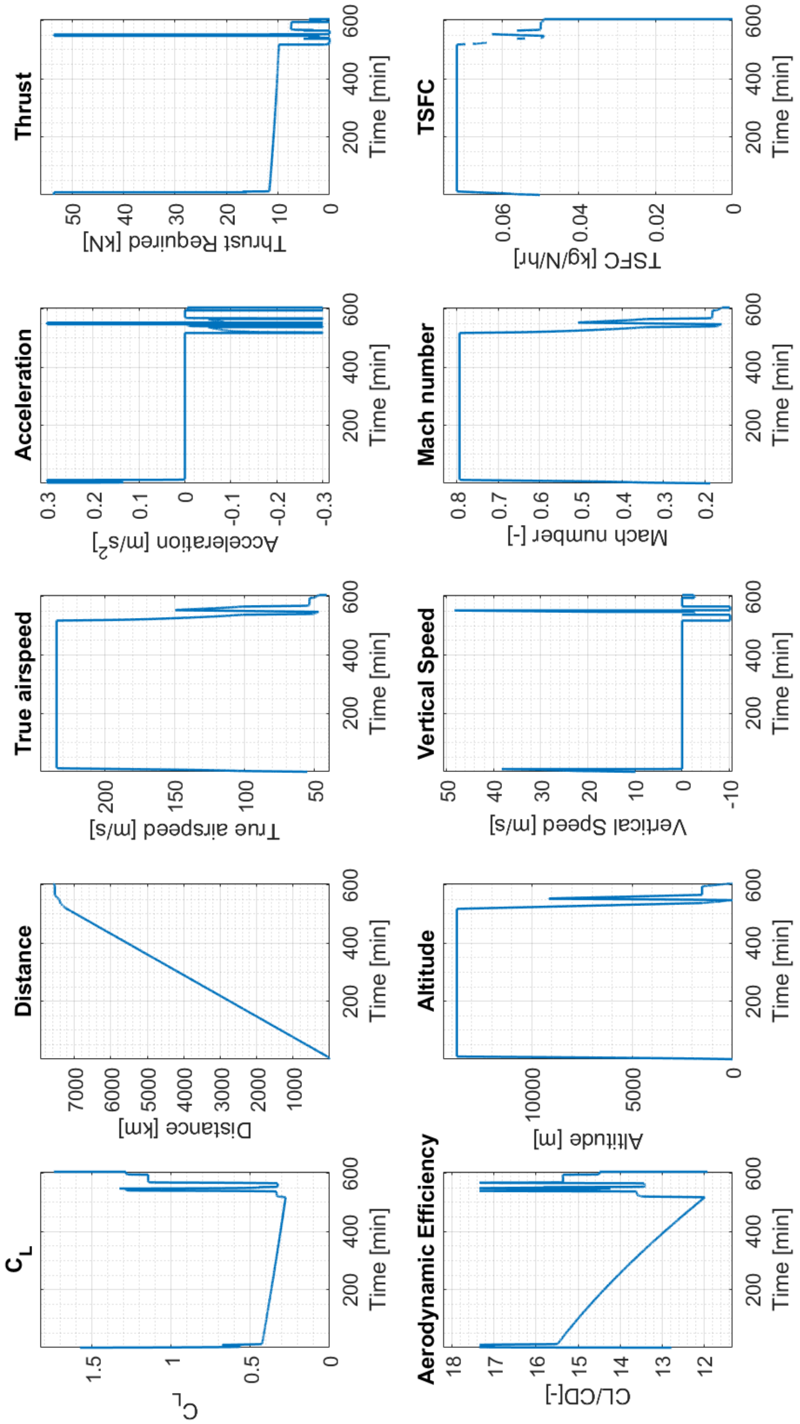


Figure A.5: MRBJ Flight parameters.

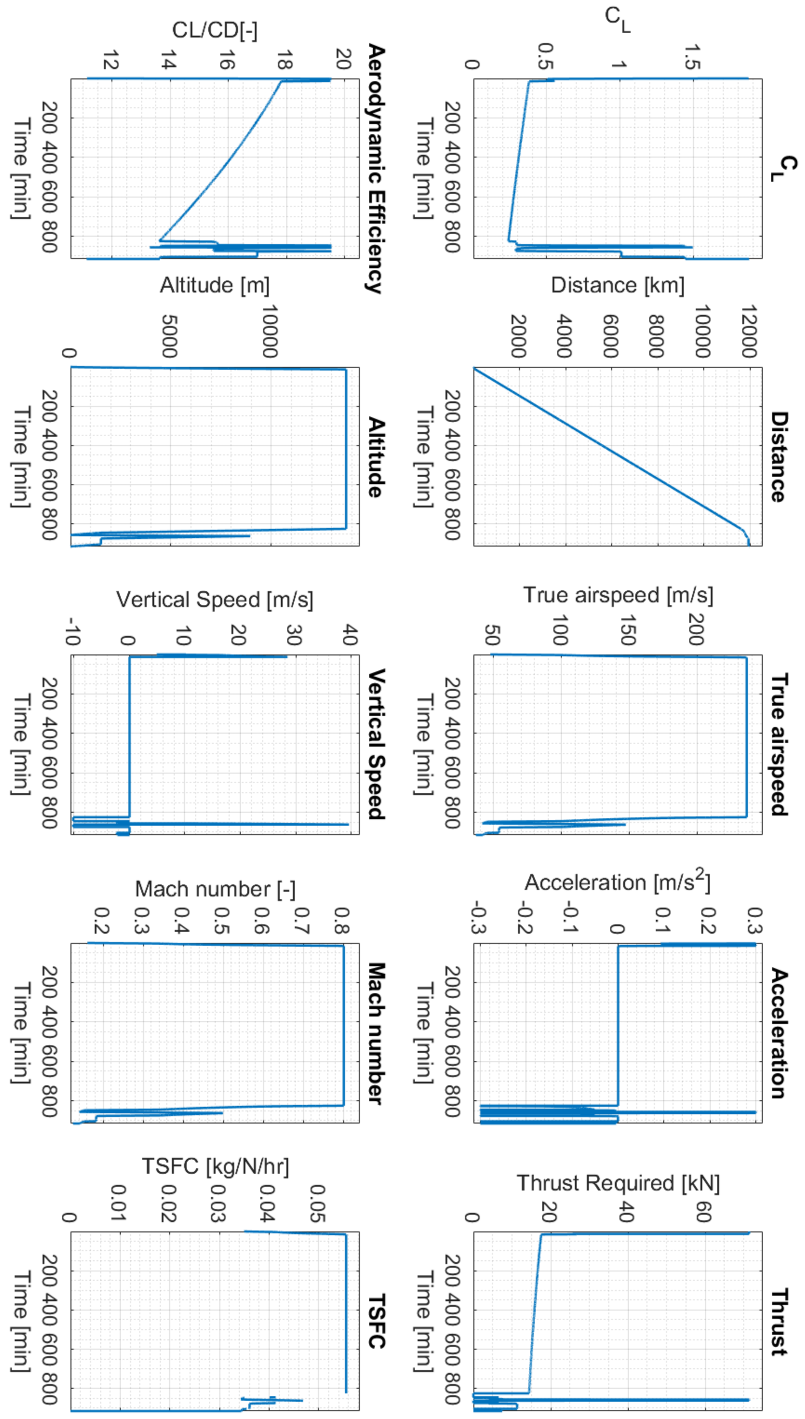


Figure A.6: LRBJ Flight parameters.

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List of Symbols

Variable	Description	SI unit
A	Area	m^2
a	Annuity rate	-
B	Burden factor	-
b	Wing span	m
BF	Block Fuel	kg
BTS	Block Time Supplement	h
C_{AC}	Aircraft cost	€
cc	Crew complement	-
C_{fuel}	Fuel cost	€
C_{D_0}	Zero-lift drag coefficient	-
$C_{D_{0_{fus}}}$	Zero-lift drag coefficient, fuselage	-
C_L	Lift coefficient	-
$C_{L_{LNDmax}}$	Max lift coefficient, landing	-
$C_{L_{TOmax}}$	Max lift coefficient, take-off	-
$C_{mainLab}$	Cost of labour per hour	€/h
$C_{mainParts}$	Cost of parts per hour	€/h
C_{RDTE}	Cost of RDTE	€
D_{fus}	Fuselage diameter	m
DOC_{crew}	Crew Direct Operating Cost	€
DOC_{fees}	Fees Direct Operating Cost	€
$DOC_{fees,ap}$	Airport fees Direct Operating Cost	€
$DOC_{fees,ground}$	Ground Handling Direct Operating Cost	€
$DOC_{fees,nav}$	Navigation Direct Operating Cost	€
DOC_{flight}	Direct Operating Cost per Flight	€
DOC_{fuel}	Fuel Direct Operating Cost	€

Variable	Description	SI unit
DOC_{HSI}	Hot Inspection Direct Operating Cost	€
DOC_{man}	Maintenance Direct Operating Cost	€
$DOC_{man,af}$	Airframe Direct Operating Cost	€
$DOC_{man,af-eng}$	Airframe/engine Direct Operating Cost	€
$DOC_{man,eng}$	Engine Direct Operating Cost	€
$DOC_{man,per}$	Personnel Direct Operating Cost	€
DOC_{OH}	Overhaul Direct Operating Cost	€
DOC_{own}	Ownership Direct Operating Cost	€
DOC_{TOT}	Total Direct Operating Cost	€
$DOC_{TOTflight}$	Total Direct Operating Cost per Flight	€
DP	Depreciation Period	-
DT	Yearly forced downtime	h
FC	Flight Cycle	-
f_{ease}	Maintenance man-hours per flight hour	-
f_{inf}	Inflation factor	-
f_{ins}	Insurance factor	-
f_{IOC}	IOC factor	-
f_{mat}	Material factor	-
F_{mf}	Ease of maintenance factor	-
f_{rv}	Residual Value factor	-
FT_{TOT}	Total Flight Time	h
$f_{usd2eur}$	USD-EURO conversion factor	-
h_{cab}	Cabin height	m
IOC	Indirect Operating Cost	€
IR	Interest Rate	-
K	Induced drag coefficient	-
K_{af}	Airframe factor	-
K_{gr}	Ground charge reference price	€/kg
K_{lnd}	Landing charge reference price	€/ton
K_{nav}	Unite rate of charge	€
K_{pax}	Passenger charge reference price	€/pax
K_{sec}	Security charge reference price	€/pax

Variable	Description	SI unit
K_t	Terminal charge reference price	€
L/D	Lift-to-Drag ratio	-
L_{fus}	Fuselage length	m
LND_{dist}	Landing distance	m
LR	Labour Rate	€/hr
$\dot{m}$	Mass flow rate	kg/s
M_{af}	Airframe mass	kg
M_{empty}	Empty mass	kg
M_{eng}	Engine mass	kg
M_{fuel}	Fuel mass	kg
M_{pc}	Payload & Crew mass	kg
M_{pl}	Payload mass	kg
M_{TO}	Take-off mass	kg
$MTOW$	Maximum Take Off Weight	kg
N_{eng}	N° of engines	-
N_{fa}	N° of flight attendants	-
N_{flight}	N° of flights	-
N_{fo}	N° of first officers	-
N_{pax}	N° of passengers	-
N_{pil}	N° of pilots	-
N_{seat}	N° of seats	-
$OPEX$	Operational Expenses	€
$OPEX_{flight}$	Operational Expenses per flight	€
$OPEX_{hour}$	Operational Expenses per hour	€
$OPEX_{year}$	Operational Expenses per year	€
P_{AC}	Aircraft price	€
P_{ENG}	Price per engine weight	€/kg
P_{HSI}	Hot Inspection cost	€
p_i	Regression coefficient	-
P_{OEM}	Price per airframe weight	€/kg
P_{OH}	Overhaul cost	€
POT	Potential yearly operation time	h

Variable	Description	SI unit
P_{tkt}	Ticket Price	€
$P_{tkt_{base}}$	Baseline Ticket Price	€
R	Range	km
ROC_{max}	Maximum Rate Of Climb	ft/min
S	Wing Surface	m^2
S_{fa}	Flight attendant salary	€
S_{fa_h}	Flight attendant salary per hour	€
S_{fo}	First officer salary	€
S_{fo_h}	First officer salary per hour	€
S_p	Pilot salary	€
S_{p_h}	Pilot salary per hour	€
S_{wet}	Aircraft wet surface	m^2
T	Thrust	kN
T_{block}	Block Time	h
TBO_{HSI}	Time Between Overhaul - HSI	h
TBO_{OH}	Time Between Overhaul - Overhaul	h
T_f	Flight time	h
T_{max}	Maximum Thrust	kN
TO_{dist}	Take-off distance	m
$T_{SL,static}$	Static thrust at sea level	kN
T_{spc}	Specific thrust	$kN/(Kg \cdot s)$
U	Utilisation rate	-
V_{crs}	Cruise speed	kn
$V_{EAS_{crs}}$	Cruise EAS	kn
$V_{EAS_{HSC}}$	High Speed Cruise EAS	kn
$V_{EAS_{stall}}$	Stall EAS	kn
w_{cab}	Cabin width	m
z_{crs}	Cruise altitude	ft
z_{HSC}	High Speed Cruise altitude	ft
$\Delta_{seat-fus}$	Lateral distance seat-fuselage	m
Φ_{eng}	Engine diameter	m
ρ	Air density	kg/m^3

List of Acronyms

ACRONYM	Extended Name
AEA	Association of European Airlines
AM	Airframe Mass
APU	Auxiliary Powe Unit
BJ	Business Jet
BPR	ByPass Ratio
BTS	Block Time Supplement
CAGR	Compound Annual Growth Rate
CeRAS	Central Reference Aircraft data System
CS	Clean Sheet
CW	Crew
DOC	Direct Operating Cost
DP	Depreciation Period
DR	Design Range
DT	Yearly Forced Downtime
EASA	European Union Aviation Safety Agency
EBAA	European Business Aviation Association
EFIS	Electronic Flight Instrument System
EICAS	Engine Indicating and Crew Alerting System
EPR	Engine Pressure Ratio
FADEC	Full Authority Digital Engine Control
FC	Flight Cycle
FT	Flight Testing
HPt	High Passengers transported
HSI	Hot Section Inspection

ACRONYM	Extended Name
HYPERION	HYbrid PERformance SimulatION
IATA	International Air Transport Association
ICE	Internal Combustion Engine
IOC	Indirect Operating Cost
IR	Interest Rate
ITT	InterTurbine Temperature
LDN	Landing
LPt	Low Passengers transported
LR	Long Range
LRBJ	Long Range Business Jet
LRu	Long Range utilisation
MR	Medium Range
MRBJ	Medium Range Business Jet
MRu	Medium Range utilisation
MTOW	Maximum Take Off Weight
NBJ	New Business Jet
NPt	Normal Passengers transported
OEI	One Engine Inoperative
OEM	Original Equipment Manufacturers
OH	OverHaul
OPEX	Operational Expenses
PL	Payload
POT	Potential yearly Operation Time
PRM	Person with Reduced Mobility
RF	RetroFit
SAF	Sustainable Aviation Fuel
SEA	Società Esercizi Aeroportuali
SMP	Sizing Matrix Plot
SR	Short Range
SRu	Short Range utilisation
TBO	Time Between Overhaul

ACRONYM	Extended Name
TIT	Turbine Inlet Temperature
TO	Take Off
TOC	Total Operating Cost
TOM	Take Off Mass
TUB	Technische Universität Berlin
ULR	Ultra Long Range
UNIFiER-19	commUNIty FrIendly minilinER

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