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Executive Summary of the Thesis

Business Jet Conceptual Design: A Cost-Driven Approach

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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1. Introduction

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 significant growth.

In this context, there is a strong interest in achieving ambitious goals, such as being more environmentally and economically friendly, and looking to move forward to develop new solutions. The latest Aviation Outlook proposed by EUROCONTROL [4] 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 by proposing a MidSize BJ with the capability to perform, if requested, long-haul routes.

2. Business Jets Market Analysis

This sector is strongly linked to business and the world of work, allowing thousands of people to travel and reach places where, for obvious reasons, it is impossible to get to by using a common airliner. The increase in the use of BJs seems to be constant for the coming years, with a 1.1 % per year growth [4].

As the Business Aircraft family includes a considerable number of models with different performances and specifications, a division into categories based on size and installed propulsion has to be carried out.

2.1. Business Jet fleet by type

The Business Aircraft could be divided according to their size and installed propulsion. Regarding the first criterion, BJs are categorised into seven classes: very light jets, light jets, midsize jets, super midsize jets, large jets, long-range jets and bizliners. These classes range from a MTOW of 4 000 kg to 45 000 kg for the Long-Range jets. Obviously, larger BJs bring

better performance (e.g. range) but have operational limitations (e.g. inability to operate at small airports).
Regarding the division on the installed propulsion, business aircraft are divided into piston, turboprop and jets. The most widespread in the jets category, followed by turboprops. Despite jets being the most popular choice, in Europe, the ratio between private jets and turboprops is around 2:1. A turboprop aircraft provides numerous advantages, including lower fuel consumption and the capability of landing on short runways, on grass or gravel, but at the cost of a lower cruise speed.

2.2. BJs fleet in Europe

The BJs in Europe are experiencing an outstanding period of growth and renewal and, referring to the latest EBAA fleet report [2], there is a based fleet of 3 856 aircraft, with a predominance of Business Jets over Business Turboprops. Figure 1 helps to visualise better how the aircraft categories are distributed.

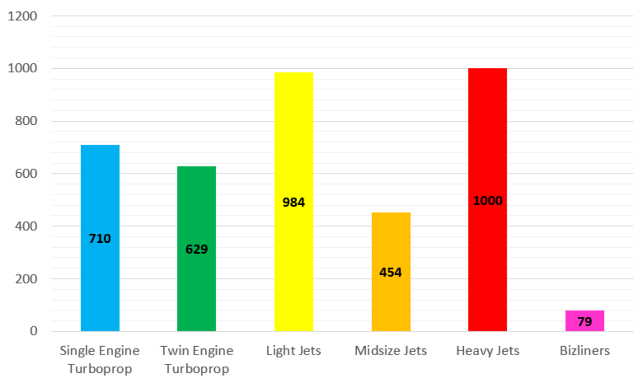

Figure 1: Business A/C categories distribution.

Concerning the division of the European Fleet from the OEMs point of view, there is a domination by Textron Aviation, both in jets and turboprops aircraft. Other important jet manufacturers are Bombardier, Dassault Aviation, Gulfstream and Embraer.
Regarding the country fleet distribution, most BJs are in Germany, France and UK, whereas Italy took 5th place with 195 aircraft registered. The ranking is also reflected in the most frequented destinations; at the top, there is Paris Le Bourget (FR), followed by Geneve (CH) and Farnborough Civ (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.

2.3. BJs European fleet by activity

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. A significant part is dedicated to Air Taxi services and private companies (i.e. A/C management and branded charter). Moreover, a conspicuous share is under the private ownership category.
Data from CE Delft [3] evidence how the highest percentage is in flights between 250 and 500 km, i.e. 24 % of all flights.

3. Business Jet Preliminary Sizing

This section proposes a methodology for the preliminary sizing of a BJ using Hyperion [6], a tool developed by DAER (PoliMI) that allows for obtaining preliminary aircraft sizing by inserting several inputs.
Two aircraft are considered to validate Hyperion for the BJs, the light jet Embraer Phenom 300E and the medium-size Cessna Sovereign +.

3.1. Ad-Hoc Historical Regressions

Hyperion uses several historical regressions to estimate preliminary A/C sizing. Aiming to obtain reliable results, two regressions are modified. The engine mass estimation is achieved using a quadratic regression by collecting numerous engine models adopted in the BJs field; the mathematical formulation is shown in Equation 1.

$$M_{eng} = p_1 \cdot T_{max}^2 + p_2 \cdot T_{max} + p_3 \qquad (1)$$

Regarding the airframe mass, only a coefficient in the pre-existing Hyperion regression is tuned. The formulation is shown in Equation 2.

$$M_{empty} = K_{af} \cdot (A \cdot M_{TO}^C) \qquad (2)$$

3.2. Validation and results

The validation of Hyperion for the BJs is executed by two different approaches. Retrofit sizing (RF) is obtained when the wing surface and airframe mass are constrained, whereas Clean Sheet (CS) sizing is when the wing surface and airframe mass are unconstrained. Results are herein shown in Table 1 and Table 2.

	A/C_{real}	A/C	E [%]
M_{TO} (RF)	13 959 kg	14 026 kg	+ 0.5
M_{TO} (CS)	13 959 kg	13 534 kg	- 3.1
S [m^2]	50.4	53.2	+ 5.6
b [m]	22.04	22.64	+ 2.7

Table 1: RF and CS result for Cessna.

	A/C_{real}	A/C	E [%]
M_{TO} (RF)	8 415 kg	8 388 kg	- 0.3
M_{TO} (CS)	8 415 kg	8 581 kg	+ 1.9
S [m^2]	28.5	42.7	+ 49.8
b [m]	15.91	19.47	+ 22.4

Table 2: RF and CS result for Embraer.

Based on the results, Hyperion succeeds in getting precise sizing for the RF, whereas CS sizing correctly estimates the mass breakdown but oversizes the wing area for the Embraer. A possible explanation is that the software tends to obtain less reliable data with small A/C, probably due to stringent stall speed and landing distance requirements that tend to increase the wing area obtained via the aircraft's SMP.

3.3. Sensitivity Analysis

A sensitivity analysis on several relevant parameters is conducted to evaluate and explore how new aeronautical technologies, such as structure, aerodynamics and propulsion, may benefit the business jets industry. The parameters are: C_{D_0}, BPR, Range, Cruise Speed and Airframe mass. The C_{D_0} and range sensitivity analysis are now presented.

3.3.1 Sensitivity analysis on C_{D_0}

A sensitivity analysis on zero-lift drag coefficient is conducted as an increase in it leads to higher thrust required, i.e. fuel consumption and the consequent rise of engine mass, leading to an overall increase in all A/C masses. It is considered a reduction until 1 % of C_{D_0} using CS sizing to perform a realistic and reliable analysis. The results are shown in Table 3 only for the Cessna since analogous results are present for the Embraer.

	A/C	A/C_{mod}	Δ [%]
M_{TO} [kg]	13 534	13 042	- 3.6
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 3: C_{D_0} sensitivity analysis for the Cessna.

It is noticeable that a reduction of the C_{D_0} leads to a general reduction of the M_{TO} since there is a drop in aircraft friction.

3.3.2 Sensitivity analysis on the Range

An analysis of how an increase in the BPR could benefit the range is now presented. In other words, a new BPR is set, and the same aircraft weight is pursued by increasing the range. Table 4 presents the results for the Cessna, whereas Table 5 presents the results for the Embraer.

BPR_{incr}	A/C	A/C_{mod}	Δ [%]
+ 0.5	5 844 km	6 005 km	+ 2.7
+ 1.0	5 844 km	6 196 km	+ 5.7
+ 1.5	5 844 km	6 382 km	+ 8.4

Table 4: Range/BPR analysis for the Cessna.

BPR_{incr}	A/C	A/C_{mod}	Δ [%]
+ 0.4	3 908 km	4 075 km	+ 4.1
+ 0.9	3 908 km	4 229 km	+ 7.6
+ 1.4	3 908 km	4 374 km	+ 10.6

Table 5: Range/BPR analysis for the Embraer.

It is visible how an increase in the BPR brings significant benefits, such as a rise in the nominal range up to 500 km. The main drawback of a higher BPR is the larger engine inlet sizes.

4. Conceptual Design of a Mid-Size Long-Range Business Jet

As seen in Section 2, the business companies operate mainly in short- and medium-haul sectors, but long-range routes are still requested, leading to equip themselves with one or more long-hail A/C. The idea is to propose a MidSize BJ with the capability, if requested, to perform long-range routes with lower ownership and operating cost than a standard long-range BJ. The proposed name for the aircraft is NBJ (i.e. New Business Jet).
The starting point to size the NBJ is an existing MidSize BJ, the Dassault Falcon 2000, which is sized through a Clean Sheet sizing using Hyperion. The A/C obtained is called MRBJ (i.e. Medium Range BJ). After that, several aerodynamics, propulsion and structure improvements are applied to the MRBJ, obtaining an improvement version called MRBJ-EA. Table 6 shows the comparison between these two aircraft.

	MRBJ	MRBJ-EA	Δ [%]
M_{TO} [kg]	19 671	15 821	- 20.3
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
T_{max} [kN]	59.5	45.3	- 23.8

Table 6: Comparison between MRBJ and MRBJ-EA.

Before starting with the NBJ sizing, the cabin layout is decided, a fundamental aspect in the BJ sector. The layout chosen presents 6 standard seats and 4 comfort seats, leading to 10 seats and 5 beds. The number of beds is crucial for long-range routes, as the flight is generally performed at night, and the passengers would like to sleep.
Subsequently, the NBJ sizing is performed by imposing on the MRBJ-EA a greater nominal range value, to find an aircraft that is capable to flight with 5/6 passengers for more than 6 000 nmi, a range value that can be considered as a constraint for categorising an A/C as a long-range BJ. The flight performances are the same as that of the MRBJ/MRBJ-EA, as the goal is to size an A/C as much as possible similar to a MidSize BJ. It is considered onboard 10 passengers plus 4 crew members.
The range objective is pursued by exploiting the corresponding Payload-Range diagram, deriving the range at which the NBJ may fly with 5/6 passengers.
Before obtaining the final sizing, a fuselage dimension sensitivity analysis is conducted by lengthening the fuselage and reducing its diameter. The final results reduced the fuselage's wet surface and consequently reduced the fuselage's zero-lift drag coefficient. The results are shown in Table 7, comparing the NBJ with the MRBJ on performance and aircraft mass aspects.

	MRBJ	NBJ	Δ [%]
M_{TO}	19 852 kg	23 067 kg	+ 16.2
M_{fuel}	7 854 kg	9 194 kg	+ 17.0
S	65.7 m^2	76.1 m^2	+ 15.8
C_{D_0}	0.0199	0.0190	- 4.5
L_{fus}	20.23 m	21.23 m	+ 5.0
R	7 408 km	10 225 km	+ 38.0
BPR	4.5	6.5	+ 44.4
EPR	15.00	23.25	+ 55.0

Table 7: Hyperion results - MRBJ and NBJ.

Notably, there is an increment in the M_{TO}, but leading to numerous advantages such as a higher range (+ 38.0 %) with a lesser difference in fuel onboard (+ 17.0 %). Finally, the Payload-Range diagram is presented herein in Figure 2.

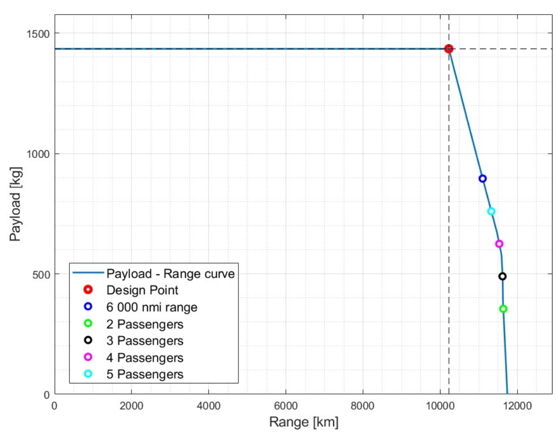

Figure 2: NBJ Payload - Range diagram.

4.1. Cost Analysis

A preliminary estimation of the operating costs of an aircraft is crucial whenever a new solution is proposed to the market.
First, an aircraft cost estimation is proposed using the "Eastlake Model" [5], leading to achieving the cost of production, A/C cost and purchase price. The results are shown below in Table 8.

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

Table 8: NBJ Cost and Price.

The next step is to evaluate the aircraft's Total Operating Cost, split into two terms: Direct Operating Cost (DOC) and Indirect Operating Cost (IOC). DOCs are evaluated by using existing methodologies for the aeronautical sector.
The DOCs are divided into five terms: fuel, maintenance, crew, fees and ownership. The sum of all terms, except the ownership ones, is named Operational Expenses, i.e. OPEX. Moreover, a "baseline" Ticket Price is computed by dividing the DOC for a flight by the number of seats available on the aircraft. The wording "baseline" indicates that the ticker sales margin is not considered.
Three different DOCs models are considered: TU Berlin method, AEA Method and Unifier-19 Method. The last, Unifier-19 [1](UN19), is chosen as it permits to obtain more reliable results in fields such as maintenance and fees. Hence, the results using UN19 for three A/C are shown in Table 9. There is the NBJ, MRBJ and LRBJ (Long Range BJ). The last is obtained through a Clean Sheet sizing of the long-range BJ Dassault Falcon 8X.

	MRBJ	NBJ	LRBJ
DOC_{fuel} [M €]	1.92	1.78	2.29
DOC_{crew} [M €]	2.07	2.96	2.98
DOC_{own} [M €]	4.33	4.64	7.24
DOC_{main} [M €]	1.80	1.82	2.46
DOC_{fees} [M €]	1.04	1.18	1.40
DOC_{TOT} [M €]	11.16	12.40	16.37

Table 9: Aircraft DOC comparison.

As visible, the NBJ and MRBJ cost are similar since there is no significant variation in the M_{TO}, whereas the LRBJ presents higher results, particularly for the Capital and Maintenance costs.

4.2. Scenario Analysis

Various scenarios, i.e. different flights, on which the NBJ, MRBJ and LRBJ are tested, evaluated and finally commented on, are now presented. The routes chosen are shown in Table 10.

Flight	Distance
Milan (IT) - Rome (IT)	470 km
Milan (IT) - London (GB)	959 km
Istanbul (TR) - Doha (QA)	2 692 km
London (GB) - New York (US)	5 554 km
Buenos A. (BR) - Mex. City (MX)	7 377 km
Milan (IT) - Buenos A. (BR)	11 172 km

Table 10: Scenarios definition.

The results are obtained using Hyperion's Mission Simulation Only function, which permits to deploy a sized A/C on a defined mission within their capabilities. The trend of DOC per flight against the flight distance is in Figure 3.

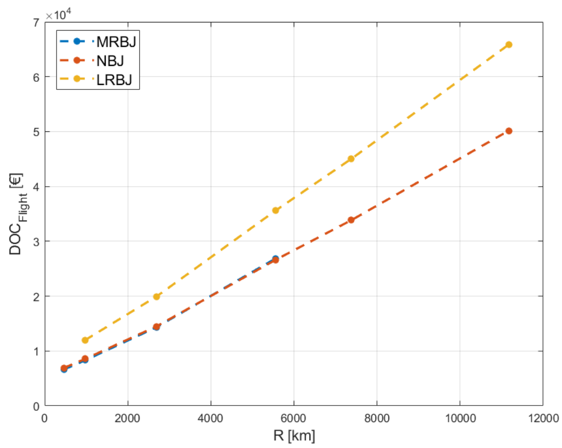

Figure 3: Variation of DOC_{flight}.

As it is visible, the NBJ and MRBJ show the same trend, whereas the LRBJ present higher operating costs per flight.

4.3. Aircraft Utilisation Analysis

The last economic analysis concerns investigating how the Operational Expenses may vary if the annual A/C utilisation changes. In other words, three different A/C utilisation are assumed: Short-Range utilisation (SRu), Medium-Range utilisation (MRu) and Long-Range utilisation (LRu). The results for the MRBJ, NBJ and LRBJ in the three utilisation are presented below in Table 11.

SRu	MRBJ	NBJ	LRBJ
DOC_{flight} [€]	10 176	10 379	19 543
$OPEX_{flight}$ [€]	5 543	5 354	9 238
MRu	**MRBJ**	**NBJ**	**LRBJ**
DOC_{flight} [€]	10 648	11 174	21 528
$OPEX_{flight}$ [€]	5 856	5 876	10 349
LRu	**MRBJ**	**NBJ**	**LRBJ**
DOC_{flight} [€]	11 163	12 088	23 938
$OPEX_{flight}$ [€]	6 196	6 476	11 698

Table 11: Utilisation results comparison.

The Operational Expenses for the MRBJ and NBJ are similar, whereas the LRBJ presents in all utilisation higher operating costs. Finally, the three utilisation are shown and compared only for the NBJ in Table 12, to understand if one utilisation or another presents significant economic advantages.

	SRu	MRu	LRu
DOC_{flight} [€]	10 379	11 174	12 088
$OPEX_{flight}$ [€]	5 354	5 876	6 476
$P_{tkt_{base}}$ [€]	1 038	1 118	1 209

Table 12: NBJ Utilisation analysis results.

It can be deduced that as annual long-haul flights increase, annual and per-flight operating expenses increase. Despite this increase, the difference between uses is not so marked, indicating that the A/C, if used at long range, does not have major economic disadvantages compared to a more short-range use.

5. Conclusion

The work carried out in this thesis can be summarised in three main points:

- The BJ sector is highly segmented in terms of aircraft size and type of installed propulsion. Moreover, most flights are short- and medium-haul, connecting mainly the crucial business European hubs.
- The sizing of a BJ using Hyperion can be carried out satisfactorily by making targeted modifications to identify the A/C category correctly. The subsequent sensitivity analysis shows how specific improvements could reduce aircraft fuel consumption and improve flight performance.
- The conceptual design presents an aircraft, the NBJ, with specifications similar to the MidSize category but with several economic advantages, representing the best option for those who require a medium-size BJ but desire performance outside of its category.

5.1. Future developments

Numerous open points remain and future developments that would make this conceptual design more concrete and competitive. In particular:

- A more in-depth analysis of how to apply propulsive and aerodynamic improvements would help find a better and more robust solution.
- 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, to correctly estimates the A/C operating costs.
- In a period where the fight to reduce emissions is a key building block for the future, a detailed analysis of how to reduce the A/C emission is essential.

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