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STUDIO E VALUTAZIONE DELLE PRESTAZIONI DI UN VELIVOLO TURBOELICA DI NUOVA CONCEZIONE

Energy Liberated to Revenue Work Ratio of an Advanced Turboprop Aircraft

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Al mio caro nonno

Con profondo affetto

RIASSUNTO

Oggigiorno le industrie aeronautiche di tutti in paesi sono interessate soprattutto al problema dell'aumento del prezzo del petrolio ed alla necessità di ridurre le emissioni di CO_2 e NO_X, obiettivo da raggiungere nei prossimi decenni. I traguardi prefissati dagli organismi internazionali possono esser raggiunti attraverso la riduzione del consumo di carburante. A tal proposito, la configurazione a turboelica dei motori potrebbe essere una tecnologia di propulsione promettente per l'immediato futuro.

L'efficienza energetica di un aeroplano può essere stimata attraverso un parametro chiamato "Energy Liberated to Revenue Work Ratio" (ETRW). Durante l'elaborazione di questa tesi, tale parametro, stimato per uno dei più avanzati velivoli a turboelica attualmente in commercio (l'Airbus militare A400M), è stato messo a confronto con l'efficienza di un aeroplano civile per medie percorrenze, il Boeing 737-800. L'Airbus A400M è risultato essere meno efficiente di quest'ultimo, a causa dell'utilizzo per cui è stato concepito e dei requisiti in termini di payload. Tuttavia, il risparmio sul consumo di carburante che deriverebbe dall'utilizzo di tale sistema propulsivo, lo renderebbe una soluzione auspicabile in nazioni in cui il prezzo del biglietto aereo conta notevolmente più di altri fattori, quale ad esempio il comfort dei passeggeri.

Oltre a queste analisi, sono state valutate anche le potenzialità del parametro ETRW per la stima delle prestazioni degli aeroplani. Innanzitutto ne è stata confermata l'efficacia per la misura dell'efficienza energetica, calcolando tramite un processo di ottimizzazione la combinazione ideale di altezza e velocità di volo che forniscono la massima efficienza. In seguito, è stata valutata la sensibilità del parametro al fattore di carico ed al degrado del motore. Come primo risultato, si è potuto constatare quanto inefficienti siano i voli effettuati a carico ridotto, come comunemente avviene per gli aerei di linea. Inoltre, si è evidenziato come sia possibile quantificare il livello di degrado di un motore effettuando semplici stime del parametro ETRW e monitorandone l'evoluzione nel tempo. Successivamente, l'utilizzo del parametro per la stima dell'impatto ambientale degli aeroplani è stato investigato in dettaglio. In particolare, si è dimostrata la relazione che intercorre tra l'ammontare lordo delle emissioni di inquinanti e le prestazioni ed utilizzo dei velivoli, fornendo un metodo di stima semplice e valido.

Sviluppi futuri del progetto di tesi possono riguardare la costruzione di modelli accurati per il calcolo del degrado del motore e la stima delle emissioni. Infine, sarebbe interessante valutare l'utilizzo dei velivoli turboelica per uso civile a percorrenza media e/o lunga, oltre a riconsiderare l'utilizzo della configurazione propfan.

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ABSTRACT

Nowadays, the main concerns of the aviation industry worldwide are increasing fuel price and the need to reduce carbon dioxide and NO_x emissions during the next decades. These two objectives can be achieved simultaneously by improving the fuel consumption of aviation engines. For this reason, the turboprop configuration may be a promising propulsion technology for the future.

The energy efficiency of an aircraft can be assessed in terms of Energy Liberated to Revenue Work Ratio (ETRW). For the aim of this thesis, the engine and aircraft models for performance assessment have been developed and verified. The ETRW parameter has been calculated for the most advanced turboprop commercially available (i.e. Airbus A400M) and then compared with the efficiency of a medium range civilian aircraft, i.e. Boeing 737-800. As a main result, the Airbus A400M was found to be less efficient, mainly due to the applications and payload requirements. However, the significant decrease in fuel consumption may lead to promising applications, in particular in the BRIC area (Brazil, Russia, India, China).

In addition to the analysis of turboprop performance, the potential of using the ETRW parameter for overall performance assessment has been investigated. First, the effectiveness of the parameter for energy efficiency measurement has been confirmed by finding the optimum altitude-speed combination for maximum efficiency. Next, some analyses have been undertaken to assess the sensitivity of the Load Factor and the engine degradation on this parameter. The first outcome is the understanding of the extremely low efficiency of flying at part load, which is common for current aircraft operations. The second conclusion relates to the possibility of quantifying the level of degradation of an engine by looking at the evolution of the energy efficiency parameter, i.e. at the fuel burnt for a given mission profile. Moreover, the use of the ETRW for aviation environmental impact assessment has been investigated. In particular, it has been shown how the gross amount of emissions can be related to aircraft operations and capabilities, offering a simple, comprehensive and reliable way to assess aircraft emissions.

Further works can be undertaken within these domains by developing more accurate models for engine degradation sensitivity and emissions evaluation. Furthermore, the employment of turboprop engines for medium-to-long range aircraft can be further investigated, along with the possible revival of the propfan configuration.

Keywords: Aircraft Performance, ETRW, Altitude-Speed Optimisation, Degradation, Emissions

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LIST OF ABBREVIATIONS

Acronyms

A/C	Aircraft
ACARE	Advisory Council for Aeronautics Research in Europe
ATM	Air Traffic Management
BRIC	Brazil, Russia, India, China
BPR	By Pass Ratio
CEP	Coefficient Of Environmental Performance
CO_2	Carbon Dioxide
DP	Design Point
EAS	Equivalent Air Speed [m/s]
ETRW	Energy Liberated To Revenue Work Ratio
GE	General Electric
HPC	High Pressure Compressor
HPT	High Pressure Compressor
ICAO	International Civil Aviation Organisation
IPC	Intermediate Pressure Compressor
IPCC	Intergovernmental Panel on Climate Change
IPT	Intermediate Pressure Turbine
ISA SLS	International Standard Temperature Sea Level Static
LF	Load Factor
MDL	Maximum Disposable Load [kg]
MFC	Maximum Fuel Capacity [kg]
MFL	Mass of Fuel Load [kg]
MLW	Maximum Landing Weight [kg]
MMF	Mass of Mission Fuel consumed [kg]
MP	Mass of Payload [kg]
MSP	Maximum Structural Payload [kg]
MTOW	Maximum Take-off Weight [kg]
MZFW	Maximum Zero Fuel Weight [kg]
NO_X	Nitrogen Oxide
OEW	Operative Empty Weight [kg]
OPR	Overall Pressure Ratio

P&W/A	Pratt & Whitney/Allison
PFEE	Payload Fuel Energy Efficiency [kg.km/MJ]
PL	Payload [kg]
PR	Pressure Ratio
SAR	Specific Air Range [m/kg]
SE	Specific Endurance [s/kg]
SFC	Specific Fuel Consumption [kg/Ns]
TAS	True Air Speed [m/s]
TERA	Techno-economic Environmental Risk Analysis
TET	Turbine Entry Temperature [K]
TPCU	TurboProp Cranfield University model
UDF	UnDucted Fan

Formula's parameters

$\dot{m}_f$	Fuel flow	kg/s
V_∞	Flight speed	m/s
$\dot{m}$	Mass flow	kg/s
A	(revenue) / (unit payload weight and unit distance travelled)	-
AR	Aspect Ratio	-
B	(fuel cost) / (unit of energy released)	-
C_D	Drag coefficient	-
C_{Dz}	Lift independent drag coefficient	
C_f	Flat-plat skin coefficient	-
C_L	Lift coefficient	-
CN	Non-Dimensional Speed	-
D	Drag force	N
dH/dt	Rate of climb	m/s
D_i	Lift dependent drag	N
D_m	Momentum drag	N
dM	Change in aircraft mass	kg
Ds	Change in distance	m
Dt	Change in time	s
D_{WV}	Volume dependent wave drag	N
D_Z	Lift independent drag	N

E	Aircraft Aerodynamic Efficiency; Endurance	[-]; s
EI_x	Emission Index of species X	-
F_n	Net Thrust	N
g	Acceleration due to gravity (9.81 m/s^2)	m^2/s
H	Geopotential height	m
H_v	Fuel Volumetric Energy Content	MJ/l
k	Take-off, climb, descent and landing fuel fraction	-
K	Non-dimensional lift dependent drag factor	-
L	Lift force	N
LCV	Fuel Low Calorific Value (Kerosene = $43*10^6$ J/kg)	MJ/kg
M	Mach number; Aircraft Mass	[-]; kg
m_f	Fuel mass	kg
p	Pressure	Pa
P	Power	kW
q	Dynamic pressure	Pa
Q	Component interference factor	-
Q_f	Fuel flow rate	kg/s
R	Great circle distance between departure point and destination	m
RTM	Revenue Ton Miles	km
S	Surface	m^2
T	Thrust	N
T_{in}	Intake Temperature	K
u	Relative Airspeed	-
V	Velocity	m/s
V_e	Equivalent Air Speed (EAS)	m/s
V_{emd}	Minimum drag speed	m/s
V_{emP}	Minimum power speed	m/s
V_f	Fuel Volume	m^3
W	Mass flow; Weight force	kg/s; N
W_f	Final weight force	N
W_{ff}	Fuel flow	kg/s
W_i	Initial weight force	N
X	Non-dimensional range	-
Y	Lift independent drag factor	kg/m
Z	Lift dependent drag factor	m/kg

Greek's symbols

α	Angle of attack	degrees
Β	(mass of fuel carried but not consumed) / (take-off mass)	-
Γ	Gamma	-
γ_2	Climb gradient	degrees
Δ	(mission fuel mass) / (take-off mass)	-
Η	Efficiency	-
Π	Proportion of the shaft thrust over the total thrust	-
Σ	Relative density	-
Φ	Component form factor	-
Ω	Fuel ratio	-

Chapter 1 - INTRODUCTION

During the last fifty years, the energy and economic crisis and the rise in fuel prices pointed out the need for aviation alternative fuels and more optimized trajectories and aircraft design. Furthermore, environmental issues push the airliners worldwide towards new ways of reducing aviation environmental impact.

The air traffic has been forecasted to grow continuously over the next 20-30 years and the environmental concern is one of the most critical aspects of future aviation: as a consequence, several regulations will be implemented and new configurations and solutions will be developed, involving engine and aircraft design and operations, bio-fuels, economics etc.

1.1 ACARE challenges and TERA

During the last decades, several organisations have been founded in order to provide independent information about the impact of civil aviation on the environment. Among them, the International Civil Aviation Organisation (ICAO) has studied the environmental impact of aviation worldwide.

Some important outcomes and forecasts have been highlighted in the last years [1], such us:

- The aviation industry contributes for the 2% of total CO_2 emissions and 12% of transportation emissions. This contribution is expected to grow around 3-4% per year (while the average air transport traffic growth rate is 5% per year, as forecasted by the IPCC in [2])
- Similar considerations have been made for NO_X emissions and noise, with projected growth rates of around 3 % and 1.5% per year
- The overall fuel consumption increase is expected to be between 3 and 3.5% per year. On the other hand, several developments can be implemented in order to improve aircraft fuel efficiency, but they are unlikely to deliver the level of reduction necessary to stabilize or reduce emissions

Ambitious goals have been defined, regarding both operations and technology improvements.

The European Aeronautic Industry, collecting several major and thousands of small aviation companies, has developed its own future goals. The Vision 2020 (*toward Flightpath 2050* [3]) is the basic document that has been produced.

The main goals of Vision 2020 include: ensure the European industry competitiveness, provide the best products and services to world airliners, create value and attract the best people and talents. Regarding the environmental concern, the main targets are highlighted below:

- Reduce aircraft emissions of:
    - 50% (*75% until 2050*) for CO_2
    - 80% (*90%*) for NO_X
- Reduce aircraft and airport noise by 50% (*55%*)
- More green life cycle, including manufacturing, operations, maintenance and disposal

In this context, several organisations and projects are born during last few years, in order to give a valuable contribution to achieve these goals. In Cranfield University, the TERA project has been implemented (Techno-economic Environmental Risk Analysis). The framework has been developed to assess novel engine technologies and undertake trajectory investigation. In order to find the best candidate for each problem, the models undertake [4]:

- Engine design-space exploration and trade-off studies
- Parametric/Sensitivity study
- Multi-disciplinary trajectory optimisation

A recent work has been undertaken by the phd student D. N. Karumbaiah in order to assess the effects of environmental policy legislations on the overall operating costs of the aircraft; the main framework has been built as shown in Figure 1-1.

Several modules have been generated to evaluate aircraft and engine performance and calculate fuel consumption, lifetime, emissions and contrails, noise, operating cost and policies effect of an input technology. They are based on real time application of physics problems or, when the previous approach is not possible, on heuristic methods.

The main core is an optimiser, which changes the variables of the aircraft and engine performance models, all interlinked in order to evaluate the overall outputs. This tool (based on a genetic algorithm) weights all the solutions to produce the best outputs, which can be the best solution regarding a single or a pareto front multi-objective set.

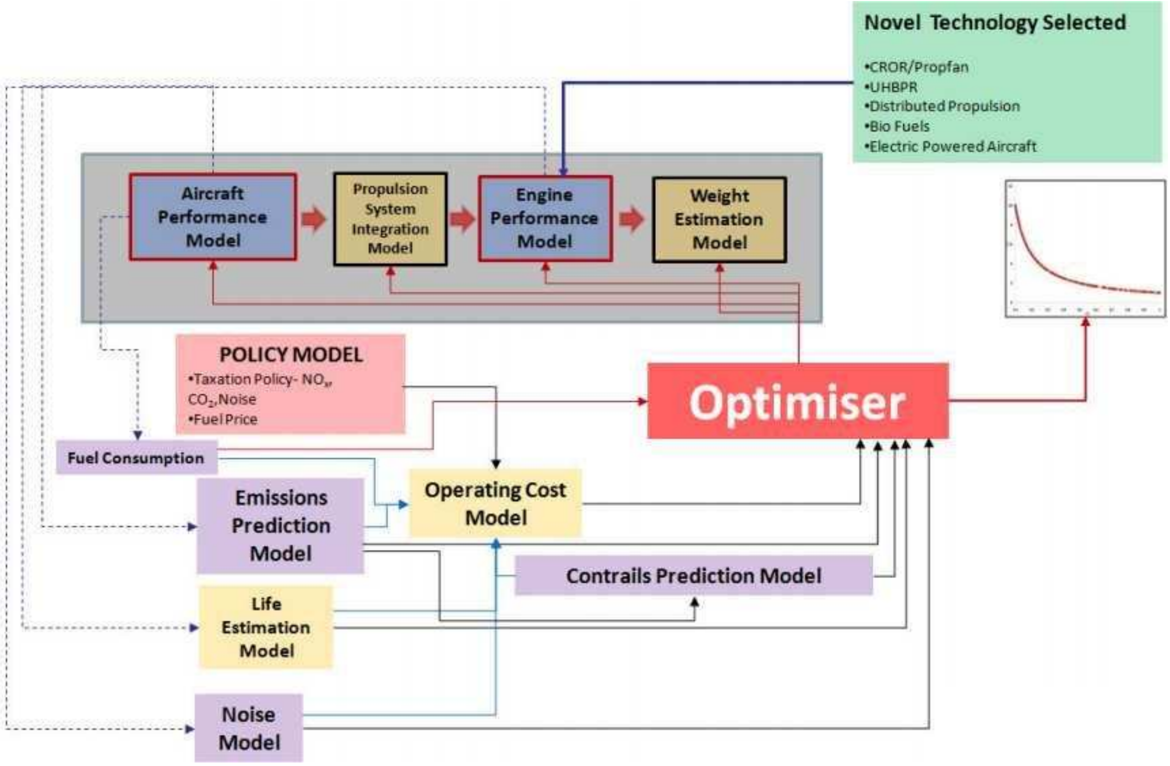

Figure 1-1 TERA framework [4]

In the context of this thesis, the integrated engine-aircraft performance module is considered, with the following aims:

- To compare aircraft performance
- To evaluate aircraft efficiency drop due to engine degradation
- To find the optimum altitude-Mach operational point
- To calculate aircraft emissions over different ranges

1.2 Summary of literature review

An interesting technology for low environmental impact is the turboprop configuration, because of the lower fuel consumption compared with turbofan engines, due to the higher overall efficiency achieved. Turboprop engines are currently installed mainly on regional passenger aircraft and on big cargo aircraft. Several issues limit the employment of these engines on medium-to-long range commercial aircraft: low speed achievable (i.e. longer time of flight), noise, passenger perception of the danger. However, the increase in fuel price, due to the recent economic crisis, moves the aviation companies towards more fuel efficient aircraft, raising the interest for turboprops.

Airbus A400M has been chosen in order to evaluate overall turboprop powered aircraft performance, even if its design features don’t allow its use as a civilian passenger aircraft. In order to assess aircraft performance, the energy efficiency method chosen is based on the Energy Liberated to Revenue Work Ratio (ETRW). This parameter quantifies aircraft performance by taking into account fuel energy and payload carried over a given range.

The calculations made in the context of this thesis show how the A400M is less efficient than common medium range civilian aircraft (i.e. Boeing 737-800). Nevertheless, this lack in efficiency is mainly due to the applications and payload requirements of the A400M and not to the engine performance. This consideration leads to the idea to install turboprops on medium range aeroplanes. Even if passengers’ perception of these engines is quite negative, in particular because of noise and blade-off danger, a significant decrease in fuel consumption can lead to lower tickets prices. This consideration is particularly important in countries like Brazil, Russia, India or China (BRIC area), where passengers are less exigent in terms of comfort but focus more on economic issues.

1.3 Aims and objectives

The main aim of this thesis is to understand the potential and limitations of the turboprop configuration for civilian purpose. As a case study, it has been chosen to evaluate the overall performance of the A400M, based on ETRW calculation. Furthermore, an important condition to be found is the operational altitude-speed combination which gives the best energy efficiency of the aircraft, in order to assess the effectiveness of this parameter for aircraft performance assessment.

In addition, it has been found interesting to undertake a sensitivity analysis of the behaviour of this parameter when the aircraft flies at part load, as usually most of the aircraft fly during normal operations, and when the engine degrades during the aircraft life. Moreover, another important outcome is an investigation of the employment of the ETRW for environmental performance assessment.

To sum up, the objectives of this thesis are:

- To understand aircraft and engine performance theory and how to build the integrated model, in order to assess turboprop powered aircraft performance
- To understand the concept of energy efficiency and the methods currently employed to quantify it, i.e. the Energy Liberated to Revenue Work Ratio
- To choose a relevant turboprop aircraft and an appropriate baseline, in order to compare their performance (preliminary study)
- To assess the energy efficiency in terms of ETRW of Airbus A400M and to compare the results with Boeing 737-800 performance
- To undertake an optimisation in order to find the best altitude-speed for maximum energy efficiency, in order to show how the minimisation of the ETRW parameter gives effectively the maximum Specific Air Range (SAR) of an aircraft
- To assess the sensitivity of flying at part load on the energy efficiency of the aircraft, in order to show how low efficient are current aircraft operations
- To assess the sensitivity of the engine degradation on the ETRW parameter, in order to understand the evolution of this parameter during the aircraft life
- To assess overall aircraft emissions in terms of Coefficient of Environmental Performance (CEP), in order to show how the ETRW can be employed for environmental impact estimation

1.4 Structure of the thesis

The framework of this thesis relates to the turboprop configuration potential for low emissions level. In chapter 2, the design drivers of turboprop engines have been derived, i.e. the need to increase the overall efficiency and the consequently change in structural design. The reasons for choosing the ETRW as efficiency metric have been highlighted. Then, a preliminary investigation has been done, to show the payload-range and weight capabilities of Airbus A400M and why Boeing 737-800 has been chosen as a baseline.

The Energy Liberated to Revenue Work Ratio is the parameter chosen for energy efficiency assessment. The chapter 3 summarises the literature review done, including an investigation of potential outcomes, the derivation and the factors which influence this parameter. At the end of the chapter, the usual evolution of the ETRW over the payload-range chart has been highlighted.

In chapter 4, the engine performance model of the TP400 has been presented. The model has been validated using literature data from the public domain. Then, some simulations have been undertaken in order to find the engine rating for different flight phases and interrelate the engine model with the aircraft performance model.

In chapter 5, the aircraft performance tool has been presented. The main assumptions for all aircraft models have been discussed and also the fuel planning and the mission profile.

In chapter 6, the first step has been to validate the models for the baseline and for the A400M, by comparing the literature payload-range diagrams with the simulation values. As soon as the models had been validated, the ETRW has been calculated for both the aircraft and compared at full load. Then, a Genetic Algorithm Multi-objectives Optimisation has been run to confirm the effectiveness of the parameter for aircraft performance assessment. The objective is to find the optimum altitude-speed combination, in order to obtain the minimum ETRW and the maximum Specific Air Range, at maximum payload-range condition.

Afterwards, some overall analyses on the ETRW behaviour have been undertaken for the A400M model.

In chapter 7, sensitivity analysis of the effect of flying at part load has been carried out and the comparison of the performance in relation to the baseline has been discussed.

In chapter 8, sensitivity analysis of the effect of engine degradation on the aircraft efficiency has been done. The engine has been rated for several degradation cases in order to obtain the same amount of thrust of the clean engine, for all flight phases. Then, the model has been run in order to achieve the same maximum payload and maximum economic ranges for each degradation case and the sensitivity on the ETRW has been evaluated.

Finally, in chapter 9, the possibility to exploit the ETRW parameter for aircraft emissions assessment has been investigated. Carbon dioxide and water vapour emissions have been evaluated by performing the Fuel Composition Method, in order to calculate the Coefficient of Environmental Performance.

However, the calculation of NO_x emissions has not been feasible because of a lack of data for model validation. Therefore, the evaluation of the CEP parameter is not complete. If some public domain data will be found, regarding TP400 NO_x emissions, a further work can be done: to develop the turboprop emissions model and get more accurate calculation of this coefficient, as highlighted in chapter 10. Other interesting improvements could be: the development of an engine degradation model and the assessment of the energy efficiency of a new design, i.e. to install the TP400 on a chosen civilian aircraft body and/or to evaluate the propfan configuration.

Chapter 2 - FRAMEWORK AND METHODOLOGY

The turboprop configuration and its improved overall efficiency can play an important role in the context of emissions reduction. In order to assess turboprop engine potential, the ETRW parameter has been chosen as an energy efficiency measurement. In the following chapter, the main reasons which motivate this choice have been highlighted and a preliminary investigation of the capabilities and characteristics of the A400M has been undertaken. Boeing 737-800 has been chosen as a baseline for performance comparison. Above and beyond, the potential of the propfan design and why it never appears on the market have been discussed. In addition, the methodology followed and the tools employed in this thesis have been presented.

2.1 The turboprop configuration

The main goal of future aviation is closely related to engine fuel consumption decrease. To achieve this target, the overall efficiency of the power-plant has to increase.

By definition, it is given by the product of the thermal and the propulsive efficiencies:

$$\eta_{overall} = \frac{Power_{aircraft}}{Power_{fuel}} = \eta_{thermal} * \eta_{propulsive} \tag{2-1}$$

$$\eta_{th} = \frac{Power_{airflow}}{Power_{fuel}} = \frac{\frac{1}{2}W_j V_j^2 - \frac{1}{2}W_0 V_0^2}{W_{ff} * LCV} = 1 - \frac{1}{OPR^{\frac{\gamma-1}{\gamma}}\left(1 + \frac{\gamma-1}{2}M_0^2\right)} \tag{2-2}$$

$$\eta_{pr} = \frac{Power_{aircraft}}{Power_{airflow}} = \frac{F_n * V_0}{\frac{1}{2}W_j V_j^2 - \frac{1}{2}W_0 V_0^2} = \frac{2}{1 + \frac{V_j}{V_0}} \tag{2-3}$$

Where the j index indicates the nozzle exhaust conditions (velocity V and mass flow W) and the 0 index the flight speed conditions. W_{ff} is the fuel flow, LCV the Low Calorific Value of the fuel and F_n the standard net thrust.

In order to improve the thermal efficiency, the overall pressure ratio (OPR) has to increase, leading to potential problems related to material resistance limit, weight, cost and general increase in the core size. To improve the propulsive efficiency, the exhaust velocity V_j has to decrease (i.e. to decrease the fan pressure ratio).

For a constant net thrust, the decrease of the exhaust velocity implies an increase in the required airflow, as shown below:

$$F_n = W_0 * (V_j - V_0) \tag{2-4}$$

Consequently, the BPR increases which leads to:

- fan diameter and weight increase, giving an increase in engine drag and weight (because more LP stages are needed to drive the fan)
- centrifugal constraints increase, so that it became important to increase the fan casing mass in order to contain fan blades in case of failure

These effects are critical for BPR above 15-20: consequently, one possible solution is to remove the fan casing, increasing the airflow without increase drag and mass (even if increasing blade-off danger). This concept is called turboprop configuration.

Turboprop engines have lower fuel consumption compared with turbofan and are therefore a suitable solution for low emissions. The main problem is that they fly at significantly lower Mach number than turbofan aircraft (i.e. the Mach usually doesn't exceed 0.6). This is because of the maximum achievable propeller tip speed, which cannot exceed the transonic velocity in order to avoid shock waves and losses.

For the purpose of this thesis, the energy efficiency of one of the most advanced turboprop powered aircraft available in commerce has been assessed, i.e. Airbus A400M. The parameter chosen to carry out the performance evaluation is the Energy Liberated to Revenue Work Ratio.

2.1.1 ETRW: an approach to aircraft efficiency assessment

After the Second World War, the time was the most important parameter to minimize: improvements on this direction lead to the development of the Concorde, a supersonic but fuel inefficient aircraft. After the energy crisis, the priority moves from time to fuel efficiency, a parameter that became even more important recently because of the growing environmental concern.

Several ways to evaluate aircraft efficiency have been developed by many researchers. One particular approach considers "the productivity of aviation as a product of passengers and cargo payload and the distance travelled, while the cost is examined in terms of fuel energy consumed" [5]. Two parameters can be defined from this consideration:

- The PFEE, Payload Fuel Energy Efficiency [5], in kg-km/MJ:

$$PFEE = \frac{RTM_{pax}{}^{1} + RTM_{mail} + RTM_{freight}}{V_f \ H_v} \qquad \textbf{(2-5)}$$

- The ETRW, Energy Liberated to Revenue Work Ratio [6], non-dimensional:

$$ETRW = \frac{MMF\ LCV}{MP\ g\ R} \qquad \textbf{(2-6)}$$

Where:

- *RTM* = revenue ton miles
- V_f = fuel volume
- H_v = fuel volumetric energy content
- *MMF* = mass of fuel consumed
- LCV = fuel low calorific value
- *MP* = payload mass (including passengers and cargo)
- *g* = acceleration due to gravity
- *R* = the great circle distance between departure and destination points

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[1] This term is the product of the revenue passenger miles and the weight allotment per passenger, that is 90,7 kg as an average

Both the parameters measure the energy efficiency of commercial aircraft taking into account fuel energy and payload carried over a given range.[2] They are exploited in order to compare aircraft economic and environmental performance.[3]

In this dissertation, the potential outcomes, the derivation and the factors which influence the ETRW parameter have been investigated (see chapter 3). As the mass of fuel is divided by the mass of payload carried and the range flown, a low value of the ETRW means a good use of the fuel carried, therefore high energy efficiency.

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[2] The time of flight "is not included in the fuel efficiency metric" […] "because it has varied by less than one per cent" in the last decades, while payload fuel energy efficiency gain over the same period has been important [5].

[3] In particular, the use of fuel energy content instead of its weight or volume is more appropriate when the aim is to compare the efficiency of kerosene based fuels and alternative fuels

2.1.2 Baseline and regional turboprops

The Boeing 737 series is the best-selling aircraft in the history of aviation. All 737 aircraft are short-to-medium range airplanes, with medium payload capabilities. Because of the overall performance and operations of this series and because of further considerations on its payload-range diagram and overall dimensions in comparison with the A400M (see section 2.1.3) the 737-800 has been chosen as a baseline for the aim of this thesis.

Figure 2-1 Boeing 737-800 [7]

Most of the turboprop engines commercially available are employed for regional transport; two of them have been chosen as terms of comparison with the baseline: the ATR 42-300 and the 72-210.

Figure 2-2 ATR 42-300 [8]

Figure 2-3 ATR 72-210 [9]

Several sources have been consulted in order to find available data for aircraft range, payload and fuel consumption combinations. The ETRW parameter has been calculated and the data and results are highlighted in the table and figure below.

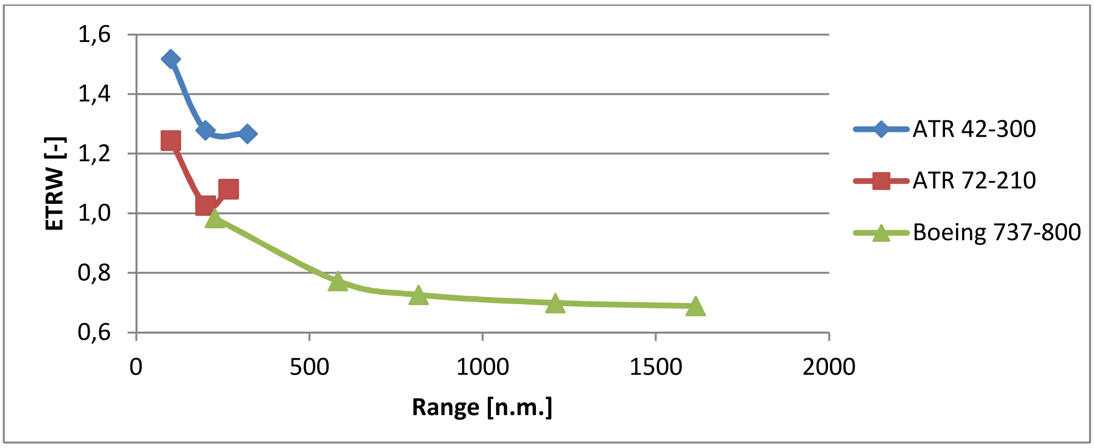


Figure 2-4 ETRW: Regional turboprop aircraft VS Boeing 737-800

Table 2-1 Regional aircraft results

	ATR 42-300			**ATR 72-210**		
Literature source	**ATR hand-out** [10]		**Aircraft Commerce** [11]	**ATR hand-out** [10]		**Aircraft Commerce** [11]
Range [n.m.]	100	200	321	100	200	267
MP [kg]	4600	4600	4600	7000	7000	7000
MMF [kg]	295	497	790	368	607	854
ETRW	1.518	1.279	1.267	1.244	1.026	1.081[4]

Table 2-2 Boeing 737-800 results

	Boeing 737-800				
Literature source	**Aircraft Commerce** [12]				
Range [n.m.]	227	582	815	1210	1615
MP [kg]	21319	21319	21319	21319	21319
MMF [kg]	2012	4052	5334	7625	10026
ETRW	0.984	0.773	0.727	0.700	0.689

---

[4] This last result for the ATR 72-210 shows an increase in the ETRW parameter, for a range which is lower than the maximum payload range achievable. This may be due to the use of different sources, which are both valuable but certainly use slightly different assumptions. This could explain the peak in the ETRW calculation.

The ETRW has been calculated for the design value of the aircraft, i.e. at maximum payload possible. The available data for Boeing 737-800 referred to part load flights, which are less efficient than full load routes, so the correct fuel consumption values have been calculated in two steps (see section 6.1 for detailed calculations):

- The literature part load flights have been simulated in order to check the accuracy of the model (in terms of fuel calculation)
- The full load routes have been simulated to find the MMF and calculate the ETRW

The performance parameter has its minimum when the aircraft flies at its maximum payload range and at full load. So the values for the regional turboprop aircraft are expected to increase after 500 n.m., while the values for the baseline aircraft are expected to grow only after 2000 n.m., i.e. the baseline aircraft is more efficient for standard airliners' medium range operations than the two ATR aircraft. However, the lower fuel consumption, the smaller dimension and higher manoeuvrability of turboprop aircraft make them more likely to be employed for very short ranges. These considerations are important because they define the available market for regional turboprops.

2.1.3 Airbus A400M

The most advanced turboprop engine available in commerce is the Europrop TP400D6, currently installed on Airbus A400M, the biggest Airbus military cargo currently employed.

Figure 2-5 Airbus A400M – Farnborough 2012 Airshow

This aircraft has been designed for logistic and tactical operations: it is able to carry very high payload (see Figure 2-7). It can take-off and land from every kind of field and perform steep climb and descent; it has high survivability and manoeuvrability and low level flight capabilities. Thanks to its advanced turboprop engines, it has highly efficient fuel consumption and it can fly over a wide range of speeds and altitudes (for more information about A400M development, operations, capabilities and specifications, see Appendix C.2.110.1C.2.1).

Looking to the payload-range diagram of the A400M (see Figure 2-6), it is possible to see how this airplane has medium-to-long range capabilities. Therefore, in order to compare it with a civilian passenger aircraft, a medium-to-long range turbofan powered airplane has to be chosen. Several aircraft are available on this range, from the Airbus 320 and 330 families to the entire Boeing 737 family.

As can be seen from the payload-range diagram comparison, the maximum payload range of the A400M is similar to the 737 series range, but much lower than the Airbus 300 series range. In addition, its payload capabilities allow the A400M to cover the whole range of the 737s, but the maximum payload of the A300 is much higher than the maximum payload of the A400M. For these reasons, the Airbus 300 series has been discarded.

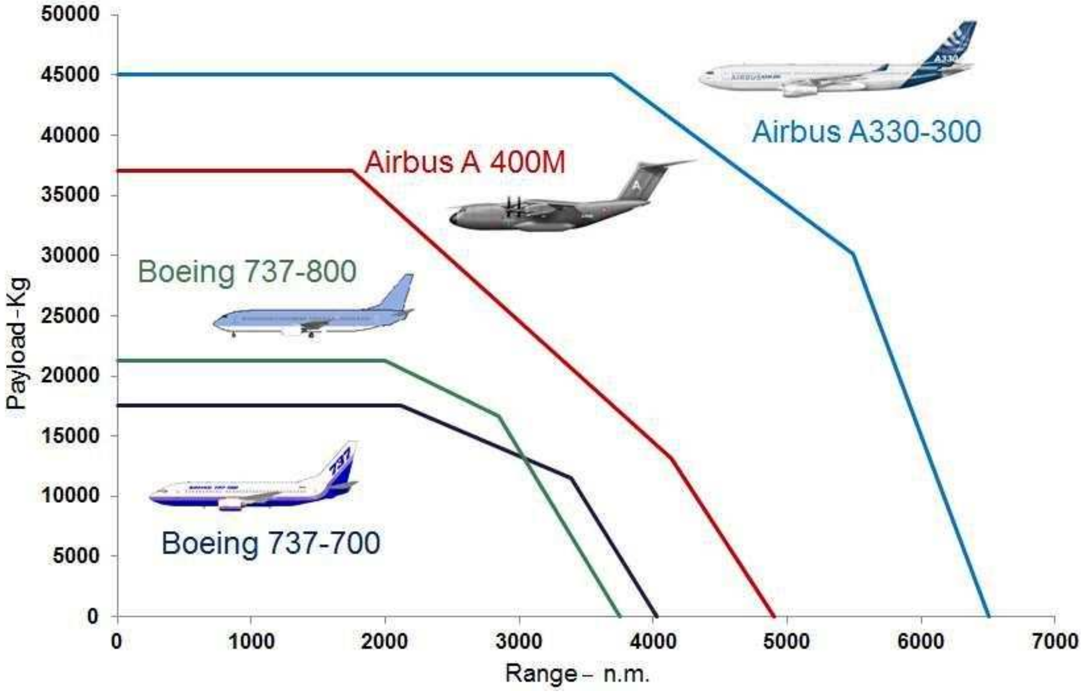
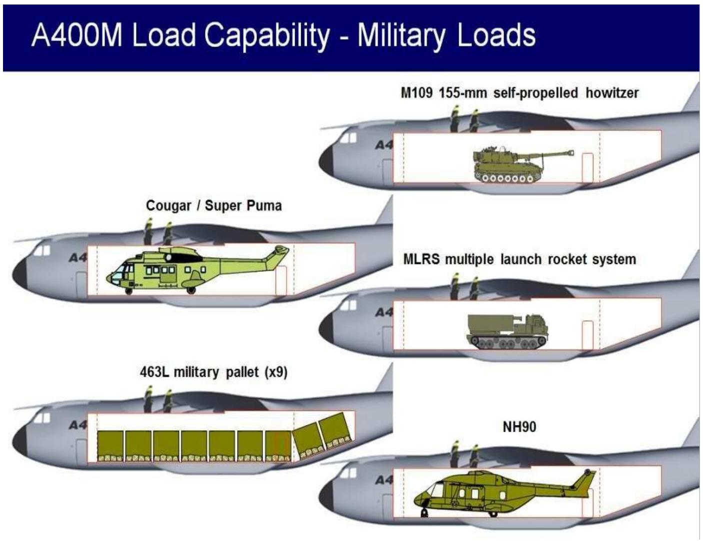


Figure 2-6 Payload-Range comparison [14]



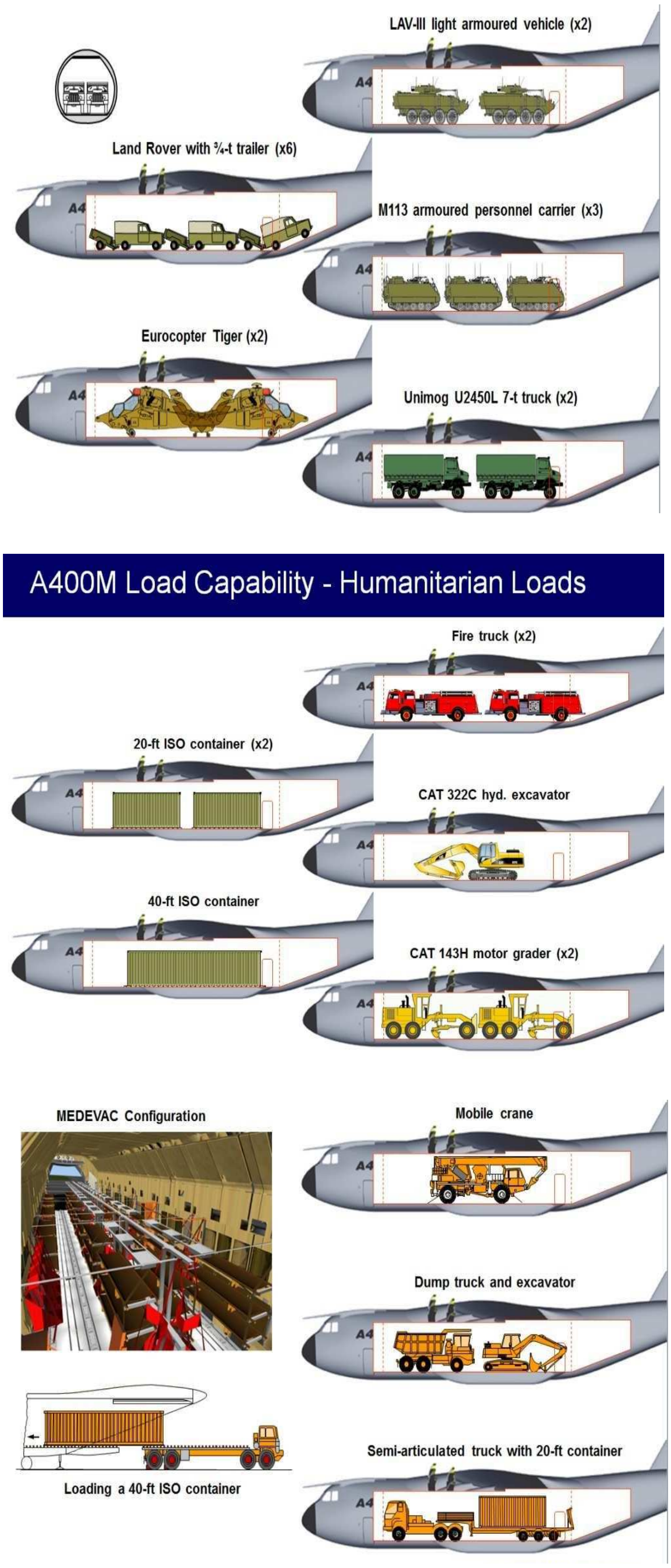


Figure 2-7 A400M cargo capabilities [13]

In addition, despite the overall external dimensions and significant payload capabilities of the A400M (Figure 2-8), the internal surface available is quite small because of its design features (i.e. short main fuselage, long tail and thick walls). As a consequence, the fuselage can only carry a limited number of passengers: the exact value has been chosen by ensuring that the cabin dimensions are sufficient to carry the same number of passengers of a medium range aircraft (Figure 2-8). Consequently, the 737-800 has been chosen as baseline: it can carry 162 passengers in the two-class configuration and 189 passengers in the only-economic configuration.

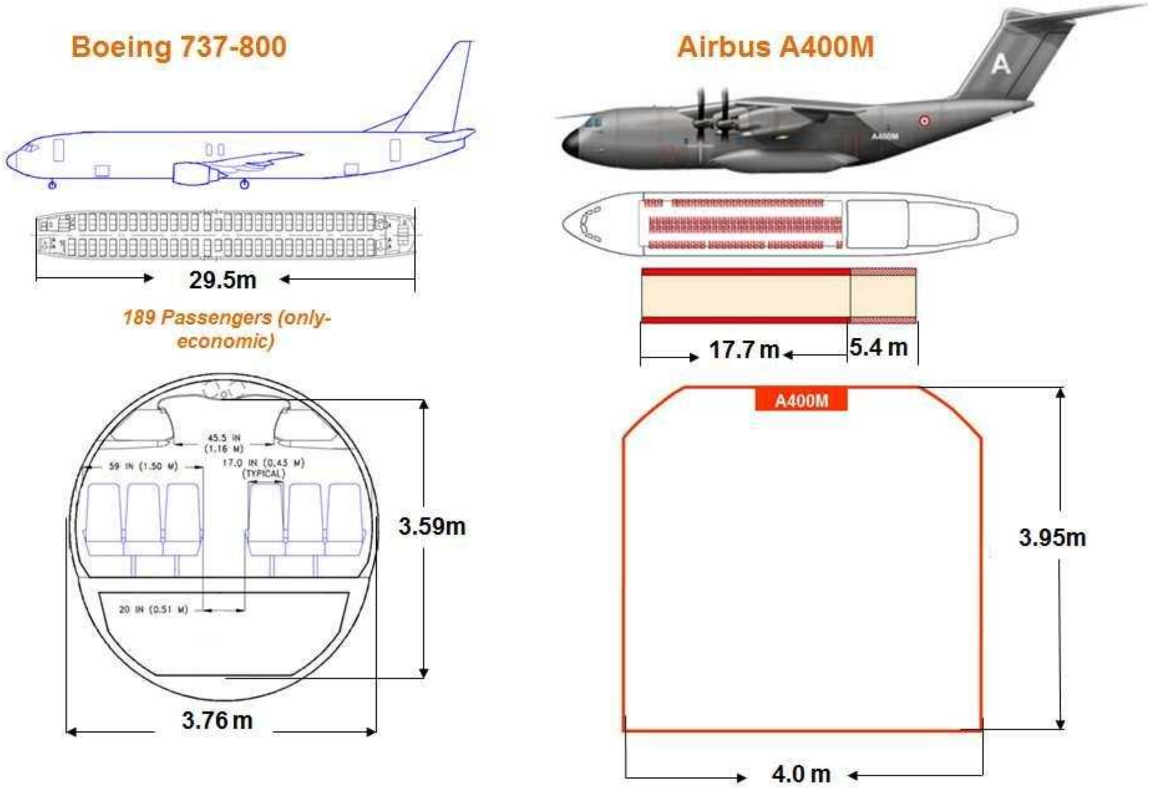


Figure 2-8 Aircraft cabin comparison [14]

General considerations can be made about A400M suitability for civilian passenger transport. The aircraft is designed for cargo operation but, as shown previously, the number of passengers which can be carried is quite small so the overall payload available cannot be fully exploited. This simple consideration leads to a less efficient aircraft than expected (see section 5 for more details).

Furthermore, the design features of the A400M, such as the long tail, the thick walls and the high wings, bring higher drag and higher weight than the baseline aircraft. The Airbus A400M is also much slower than Boeing 737-800 and so less suitable for time efficient flights (i.e. it achieves a maximum Mach of 0.72 while the Boeing exceeds 0.8).

However, the ETRW parameter generally shows good aircraft performance. Also, the turboprop engines are usually designed for lower emissions than turbofan. All these considerations lead to the possibility of installing advanced turboprop engines on civilian aircraft. Two possible designs follow: the simple installation of available turboprop engines on current aircraft, and the development of open rotors leading to the propfan configuration. The first solution is interesting because easy and inexpensive to develop and because of the reliability of ready-designed aircraft. Furthermore, it can have remarkable advantages in broad countries such as in the BRIC area, where the ticket price is one of the major passenger concerns. The second solution has been developed in the past and then abandoned because of fuel price issues, but can maybe regain attention because of the new fuel price scenario.

2.2 The propfan configuration

Propfan aircraft combine advanced turboprop performance, in particular low environmental impact (i.e. low fuel consumption), and higher velocity (i.e. lower time of flight). The engine design is a low diameter, highly loaded unducted propulsor, generally with variable pitch. It was first developed in the mid-70s by Hamilton Standard, in order to mitigate turboprop's compressibility losses at high Mach number. In the following years, two engines were developed on this basis, the GE UDF (UnDucted Fan) and the Pratt & Whitney/Allison 578DX, and two possible aircraft had been developed in the late 80s, to accommodate these engines: the Boeing 7J7 and the McDonnell Douglas MD91/92.

Regarding the engines, both of them have low fuel consumption and can achieve high Mach number and altitude. The main difference is the power transmission: in the **GE UDF** the propeller blades are spinning in opposite direction and are directly attached to the turbine, while the **P&W/A 578DX** is geared so that the propeller can rotate slower, improving the propulsive efficiency.

Figure 2-9 GE UDF [15]

Figure 2-10 P&W/A 578DX [16]

However, the UDF turbine has no stators, so that the relative velocity between each stage is doubled, making the turbine smaller, simpler and faster. The main issues related to both engines are [17]:

- noise level for passenger acceptability (in particular at take-off, showing shorter but wider noise than turbofan); the rear-mounted configuration was an attempt to solve the problem and keep noise and vibrations out the cabin

- uncontained blades, adding safety issues
- ice problems, because the small core gives less bleed air available for ice removal
- higher weight and cost, in addition to the airliners' caution towards unknown reliability of new products

Looking at the aircraft, the principal difference relates to the fact that the Boeing 7J7 is a newly designed aircraft, while the McDonnell Douglas MD91/92 are derivative solutions.

Figure 2-11 Boeing 7j7 [18]

Figure 2-12 MD-92 [19]

The **Boeing 7J7** has several new features and advantages [20]:

- twin aisle 2-2-2 configuration, so that every passenger is sat next to an aisle or a window; even with the 2-3-2 configuration this statement is still valid, because usually aircraft load factors are below 80%
- improved aerodynamics and use of composites (to reduce safety issues, because the blades shatter if they break)
- new digital data transmission system (fibre-optic signalling)
- new ice detection system, based on electro-impulse, to decrease air bleed need
- improved fuel consumption (up to 25-30% [21]), giving lower fuel burnt for the same range or higher range for the same fuel load

In spite of the obvious advantages of this aircraft, mainly related to the huge leap in fuel efficiency, the market was not ready to accept this new design. Nevertheless, many innovative features have been further developed after the project ended and are currently employed on modern aircraft.

On the other hand, the **McDonnell Douglas MD91** and **MD92** are derivate of the MD80 series, which are a well known and commonly employed aircraft. This particular approach has been the strong point of McDonnell Douglas' marketing strategy during the development of the aircraft. The main idea, the fuel price being so low, was to keep the development costs down and supply the airliners with a familiar and reliable solution [22]. However, the fuel price was at its minimum in the late 80s and in the same period Boeing started to sell several 737, equipped with the CFM56, developed by both GE and Snecma. For GE, the launch of the new UDF has been found less interesting than a strong improvement of the now popular CFM56: the project has therefore been abandoned. Furthermore, from the airliners' point of view, the fuel price was too low to justify the purchase of new aircraft of greater price and complexity than the old ones and propfan aircraft never enter the market.

Nevertheless, because of the last world economic crisis in 2008, the fuel price has never been as high as in the last years. Also, with the recent application of environmental policies, more and more efforts have to be made in order to minimise aviation impact, i.e. reduce engine fuel consumption. In this context, the propfan solution could gain visibility and finally become more attractive thereby increasing its potential to overtake aircraft already present on today's market.

2.3 Methodology and tools

In order to assess A400M performance, Boeing 737-800 has been chosen as baseline. The aircraft and the engine models were available in the Cranfield database; however, a validation procedure was undertaken using the Boeing payload-range diagram. The errors between model simulation and literature's values have been assessed and the model has been run for several payload-range combinations, in order to find the efficiency of the aircraft along the payload-range diagram, in terms of ETRW.

Then, the evaluation of Airbus A400M performance has been done. The engine model has been created and validated using data from the public domain and the rating of the engine has been found. Then, the aircraft model has been developed and validated using the payload-range diagram from Airbus Military. The ETRW has been calculated along the payload-range line and then compared with the baseline. In addition, a multi-objective optimisation has been run, in order to find the optimum altitude-speed combination for minimum ETRW and maximum Specific Air Range.

Then, some overall analyses on the ETRW behaviour for the A400M model have been undertaken: first, the effect of flying at part load on the overall energy efficiency has been considered. A sensitivity analysis of the effect of engine degradation on the aircraft efficiency has been undertaken; finally, option of using this parameter for aircraft emissions assessment has been investigated.

HERMES and TURBOMATCH software have been used [23; 24] to calculate aircraft and engine performance. Post-processing of the results and optimisation have been done in MATLAB, to estimate the ETRW for each of the above aircraft, for different payload-range combinations and engine settings.

Chapter 3 - “ETRW” FOR AIRCRAFT PERFORMANCE ASSESSMENT

The Energy Liberated to Revenue Work Ratio is an interesting energy efficiency measurement. In the following chapter, the literature review done on this parameter has been detailed. First of all, the ETRW has been derived and the potential outcomes for aircraft performance assessment have been discussed. Furthermore, the sensitivity of the load factor and the fuel carried and the evolution of the parameter over the payload-range chart have been assessed. Most of the data and formulas presented on the chapter are discussed in [6].

3.1 Economic and environmental efficiency

The economic efficiency of airlines operations relates to:

$$\frac{revenue\ generated}{cost\ of\ energy\ used} = \frac{A}{B}\left(\frac{1}{ETRW}\right) \tag{3-1}$$

Where:

- A = revenue/unit payload weight and unit distance travelled
- B = the fuel cost/unit of energy released

The terms A and B depend upon market forces and are variable during the working life of the aircraft; the ETRW parameter has been defined in the section 2.1.1 and is fixed by the aircraft’s designers. The maximisation of the revenue generated over energy cost is a balance between the cost of fuel and the cost of time. Furthermore, the market demands high performance aircraft, which implies low values of the ETRW.

In addition, it is possible to evaluate a Coefficient of Environmental Performance as the amount of emissions released per unit of revenue work performed, dependant on the ETRW:

$$CEP = \frac{emissions\ mass * LCV}{useful\ work\ done}$$

(3-2)

$$CEP = ETRW * \sum (a\ EI_{CO_2} + b\ EI_{NO_x} + c\ EI_{H_2O} + d\ EI_{SO_x} + \cdots)$$

EI_x is the emission index of the specie X and a, b, c, d, etc are constant, which depend on the fuel used and the level of technology. This relationship shows how the minimisation of the ETRW gives also low aircraft emissions.

3.2 The optimum airplane

For a given level of technology, an aircraft configuration can be defined by:

- Passengers' payload
- Range to be flown
- Engine characteristics and number
- Length of runway
- Safety requirements
- Specific cruise Mach number
- Airport limitations (wingspan, aircraft dimensions and weight, noise restrictions…)

Once these parameters have been taken into account, the design process is an optimisation involving target functions, i.e. maximum payload fraction, minimum fuel costs, minimum time, minimum emissions or contrails etc.

3.3 ETRW derivation

The ETRW depends upon the fuel burnt in order to carry a given payload for a defined range. The total mass of the aircraft M decreases while the flight progresses, because fuel is burned (m_f):

$$\frac{dM}{dt} = -\frac{dm_f}{dt} = -\dot{m}_f \tag{3-3}$$

It is possible to define the thermodynamic overall efficiency η_o using the low calorific value LCV, the thrust T and the flight speed V_∞ , as:

$$\eta_0 = \frac{T\, V_\infty}{LCV\ \dot{m}_f} \tag{3-4}$$

In cruise condition, the aircraft lift L equals the weight W and the thrust T equals the drag D, so that:

$$-\frac{dM}{dt} = -\frac{dM}{ds}\frac{ds}{dt} = -\frac{dM}{ds}\, V_\infty = \frac{\dot{m}_f}{V_\infty}\, V_\infty = \left(\frac{D}{\eta_0 LCV}\right) V_\infty \frac{Mg}{L} \tag{3-5}$$

The thermodynamic efficiency, the lift and the drag depend upon the cruise Mach number and altitude. For a given aircraft, a defined trajectory exists and gives a constant value of $\frac{\eta_0 L}{D}$, so that $\frac{dM}{ds}$ can be integrated to obtain the total fuel consumed for a defined range R:

$$\frac{MF_{cruise}}{M_{initial}} = 1 - exp\left(-\frac{D\ g\ R}{\eta_0 L\ LCV}\right) = 1 - \exp\left(-X\right) \tag{3-6}$$

Where X is the non-dimensional range.

But the overall mission includes also take-off, climb, descent and landing, so an additional amount offuel k has to be taken into account and the total mission fuel burnt MMF over the overall take-off initial mass MTO can be defined as the ratio δ:

$$\frac{MMF}{MTO} = 1 - k * exp\left(-\frac{D\ g\ R}{\eta_0 L\ LCV}\right) = \delta \tag{3-7}$$

The total mass at the beginning of the take-off MTO can be defined as:

$$\begin{aligned} MTO &= MOE + MP + MF_{NC} + MMF \\ &= ML + MMF \\ &= MZF + MMF + MF_{NC} \end{aligned} \tag{3-8}$$

Where:

- MOE = operational empty mass
- MP = payload mass
- MF_{NC} = reserve of fuel = β * MTO
- MMF = mission fuel mass
- ML = landing mass = MOE+ MP + MF_{NC} = MTO (1-δ)
- MZF = zero fuel mass = MOE + MP = ML - MF_{NC} = MTO (1-δ-β)

The main assumption is that the reserve of fuel can be defined as proportional to the initial take-off mass by a factor β.

Then, it is possible to define the fuel burnt MMF per unit of payload MP per unit of distance flown X as:

$$\frac{MMF}{MP * X} = \frac{1}{X}\frac{MMF}{MTO}\frac{MTO}{MZF}\frac{MZF}{MP} = \frac{1}{X}\frac{\delta}{1-\delta-\beta}\frac{MZF}{MP} \tag{3-9}$$

Finally, the ETRW depends on the fuel burnt for a particular mission, being:

$$ETRW = \frac{\frac{MMF}{MP * X}}{\eta_0 \frac{L}{D}} \tag{3-10}$$

This equation is exact for the conditions specified, so it doesn't depend upon the aircraft configuration.

3.3.1 Observations and parameters of influence

Several theorems have been determined, considering an aircraft cruising at constant $\frac{\eta_0 L}{D}$ for a fixed distance. Several results have been established, among which an important consideration to be made is that, at maximum payload condition, the absolute minimum ETRW occurs when the product of structural, propulsive and aerodynamic efficiencies is maximised. Also, at constant PL, increasing the MMF the aircraft flies further and further.

The "Load Factor" is defined as the ratio of the actual payload over the maximum achievable payload. Plotting the lines of constant ETRW in a normalised payload range diagram (see Figure 3-1), it can be see that "the load factor is a very important parameter for flight efficiency and that operating an aircraft over short ranges can result in very large efficiency penalties" […] "Typically, a 10% increase in LF will reduce the ETRW by about 7.5%".

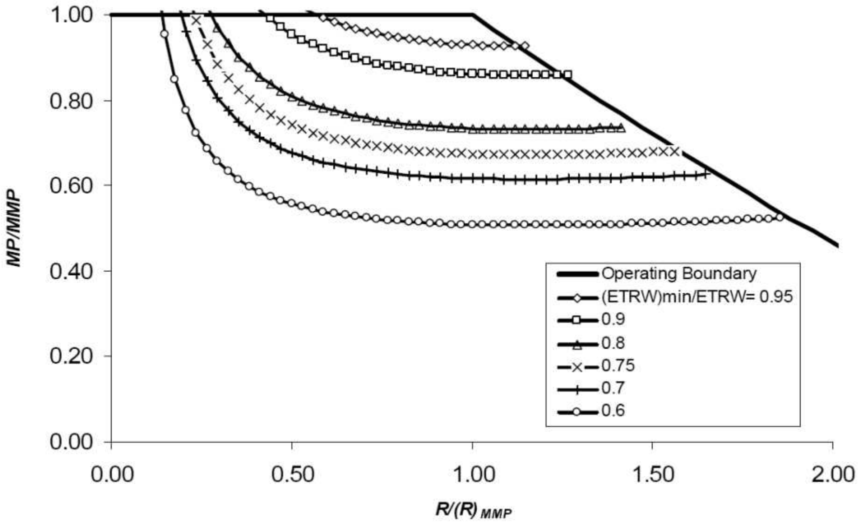


Figure 3-1 Variation of normalised ETRW with normalised range [6]

MOE/MMTO = 0.55, eps= 0.025 and beta= 0.05

Inefficient take-off, climb, descent or/and landing (inefficient air traffic management) increase the additional fuel to carry (the optimum value is around 0.025 of the cruise fuel). A 10% increase causes a 1.5% increase in the ETRW. In addition, the minimum reserve fuel is approximately 0.045 of the take-off mass for normal operation. If this value is increased by 10%, there will be a 6% increase in the MMF and consequently a 0.7% increase in the ETRW.

Table 3-1 Sensitivity of the parameters of influence on the ETRW

Parameters of influence (increased by 10%)	**Increase in ETRW**
Load Factor = PL / PL_{max}	- 7.5 %
Extra fuel consumed (optimum_eps = 0.025 * MMF)	+ 1.5 %
Minimum reserve fuel (standard_beta= 0.045 * MTO)	+ 0.7 %

3.4 Current aircraft and possible improvements

Over the last two decades, the payload fuel energy efficiency of the available aircraft has doubled. By and large, cargo and passenger operations have comparable fuel efficiency, though the former has higher payload fuel energy efficiency, due to the larger payload carried [5]. As a consequence, the ETRW for the aircraft currently in commerce is more or less constant, with an average of around 0.75 and a minimum of 0.6.

Several factors influence the value of the ETRW. Among them, the parameter is more sensitive to the payload and the fuel carried for the mission and for air traffic management (holding and diversion manoeuvres). Furthermore, the ETRW increases importantly when the range flown is small.

This is because of the higher sensitivity of short flights upon the minimum reserve fuel carried and upon inefficient air traffic management. Also, the load factor is normally around 60%[5]. The average ETRW for short flight is up to 20% higher than for long distances, where operations account for the 80% of the difference.

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[5] In 2007, for passenger aircraft, the passenger load factor was 79% while the belly-freight was only 16%. For cargo operations, it was 62%. The average overall load factor was 61% [5].

Besides, the majority of the flights is carried out inside Europe or United States, so the global fleet average ETRW is much higher than the average value for all aircraft in commerce (approximately double).

Important improvements to the current situation can be done by minimising the ETRW.

Table 3-2 ETRW future improvements

Objective	**Improvement**	**Reduction in ETRW**
Operate with the largest possible load factor	Largest number of passengers and cargo	(No data available)
Reduce aircraft structure mass	Composite materials	8-15%
Increase propulsive efficiency	Advanced turboprops and open rotors[6]	10-15%
Increase airframe lift/drag	Improved aerodynamics	(No data available)
Increase the energy per unit volume of the fuel	Bio-fuel, hydrogen, nuclear fuel...	(No data available)

A global 35% improvement in the ETRW can be achieved by a combination of all above parameters, with a peak of 50% in case of large increase in LF and a more efficient ATM.

3.5 Aircraft efficiency assessment

As explained before, the performance of an aircraft can be presented in terms of the ETRW parameter, a key indicator of the environmental impact of a particular aircraft design.

Taking into account the behaviour of an aircraft along its payload-range diagram (see Appendix B.4 for details about how the diagram is defined), it is possible to see how the ETRW changes along the payload line:

- The minimum value of the parameter is achieved at its maximum payload range; for lower ranges, the parameter is quite constant and slightly higher than the minimum

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[6] Despite the advantages, several issues related to noise and safety have to be taken into account

- For very short ranges, the air traffic operations (including diversion and hold) and the climb and descent performance affect importantly the overall aircraft performance, so that the ETRW increases
- Over the maximum payload range, the payload decreases, while the fuel consumed increases with the range; consequently, the ETRW parameter shows a perpetual increase. The aircraft became really inefficient for ranges over the maximum economical range (the ETRW going toward infinite).

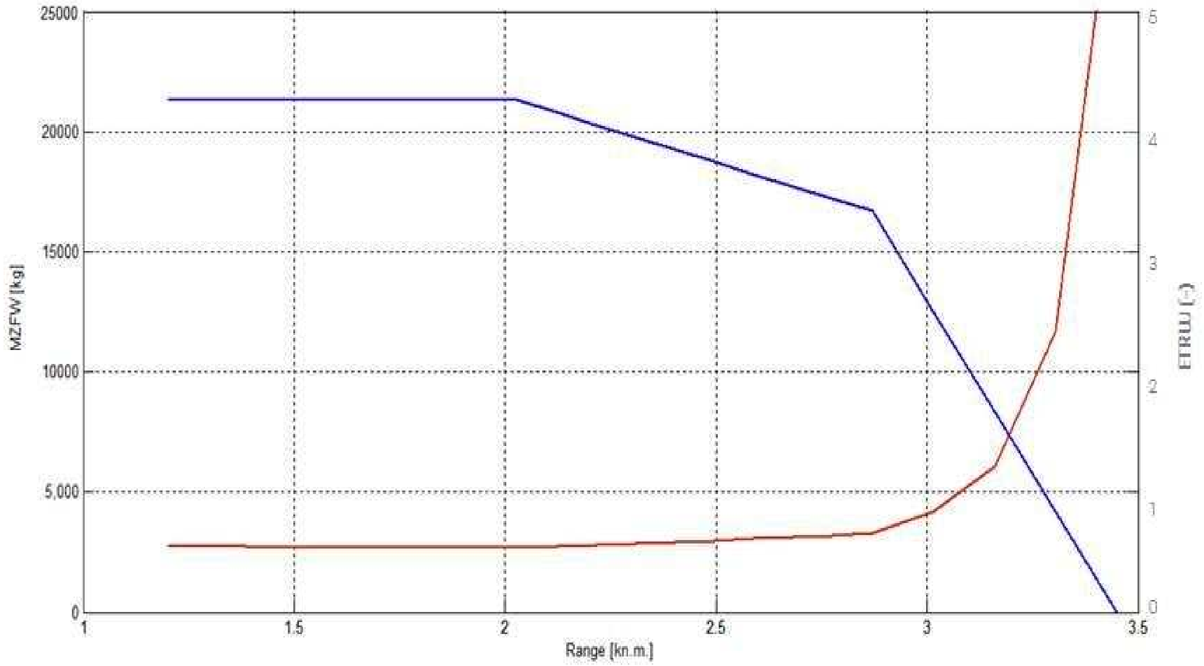

Figure 3-2 Payload-Range chart (blue) and ETRW (red) of the 737-800

Another important consideration has to be made in regard to the aircraft loading factor: the most efficient way to flight an aircraft is at full load. However, as explained in section 3.3.1, most of the flights worldwide have an average load factor around 60% (mostly passengers and luggage, without fully exploit the aircraft belly-freight capabilities). Flying at part load, for a fixed range, the payload factor on the ETRW expression decreases; also the fuel burnt decreases, because the aircraft is now lighter, but less significantly than the payload. Consequently, the parameter increases sensitively.

Chapter 4 - ENGINE PERFORMANCE MODEL

In order to evaluate aircraft performance, the aircraft module has to be linked to the engine performance module. For this purpose, two engine models are required: one for the CFM56-7B and another for the TP400-D6. The turbofan model is available on the Cranfield University database [25]. On the other hand, in order to assess the performance of the A400M, a turboprop model has been created. The validation has been done using literature data from the public domain. Then, the engine has been rated in order to find the thrust levels and TETs for each flight phase.

4.1 TPCU model description

The TPCU model has been developed from the TP400D6 engine, a twin-spool gas generator, with third coaxial shaft for power turbine, currently installed on the Military Airbus A400M.

Figure 4-1 Europrop TP400-D6

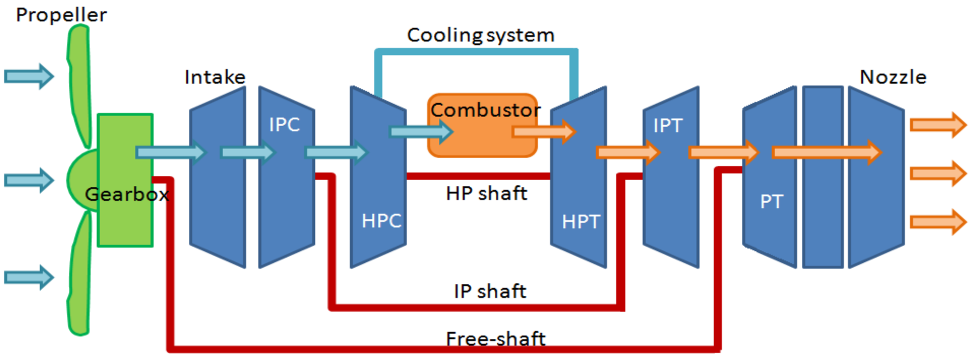

Figure 4-2 TPCU TURBOMATCH model

The overall dimensions are 3.5m (length) x 0.92m (diameter). The engine basic weight is 1860kg. The gas generator consists of 5 stages IPC, with fixed stators, and 6 stages HPC, with two rows of variable stators. The HP and IP turbines have both one stage, followed by 3 stages PT. The HP turbine is cooled.

4.2 Literature data

A series of iterations have been run to match the design point performance of the TPCU turboprop. Some input and output parameters have been found in the public domain [26-28]. Using this information, the model has been produced and the design point has been chosen, to match the requirements.

Table 4-1 TURBOMATCH model inputs

TP400D6 (and TPCU model) Input Parameters	Value
OPR	25
IP_PR	3.5
HP_PR	7.14
Cruise Mass Flow [kg/s]	26.31
Cruise Mach	0.68
Cruise Altitude [m]	9449
Propeller take-off rotational speed [rpm]	860
Propeller cruise rotational speed [rpm]	842
Propeller diameter [m]	5.33
Main cooling Air	10%

Table 4-2 TURBOMATCH target outputs

TP400D6 Output Parameters	Value
Power Output SLS [kW]	8251
Power Output Cruise [kW]	5505

4.3 Design Point and Off-Design performance assessment

The design point has been chosen at top of climb. This choice has been made because this point usually has higher non-dimensional mass flow than all other phases. Therefore, the engine intake size is also the highest and the maximum dimensions of the core can be chosen correctly.

The value of altitude and Mach are the same of the maximums for cruise, found in literature, in order to match with the input data.

The results have been validated calculating the power output of the engine for cruise and take-off TET at SLS, with errors under 2%. After several iterations, it has been possible to define an acceptable matching, changing TET and components efficiencies (which are acceptable values for the current level of technology of advanced turboprop engines).

Table 4-3 TURBOMATCH model assumptions

TPCU Assumptions	Value
Compressor Isentropic Efficiency	0.87
Turbine Isentropic Efficiency	0.92
Combustor Efficiency	0.9999
Combustor Pressure Loss	0.05
Ducts Pressure Loss	0.02
TET [K]	1245

The results and the relative errors related to the power output values (in comparison with literature data) are shown in the table below.

Table 4-4 Simulation results

Parameter	TP400D6	TPCU	Error
Power Output Cruise [kW]	5505	5607	1.85%
Power Output take-off [kW]	8251	8403	1.84%

The results for the off-design performance of the TPCU are highlighted in the figures below, i.e. the effect of altitude, ambient temperature, flight Mach number and TET on engine thrust and SFC.

Following, the total thrust (propeller plus jet) F_N and the SFC in function of Mach number and Altitude, from sea level until cruise altitude (9449m). The TET is fixed at design point condition (1245 K) and the ISA deviation is zero.

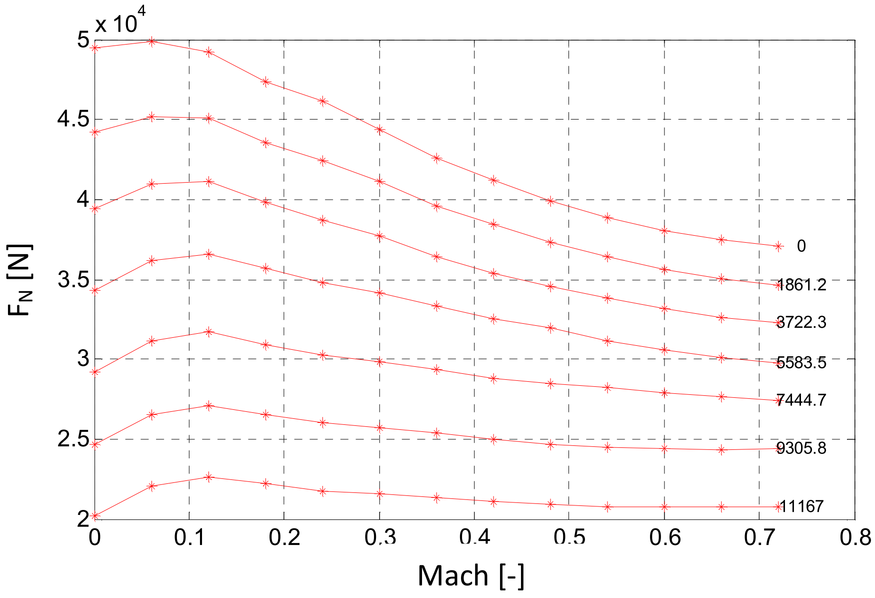

Figure 4-3 Thrust [N] over Mach for different altitudes [m]

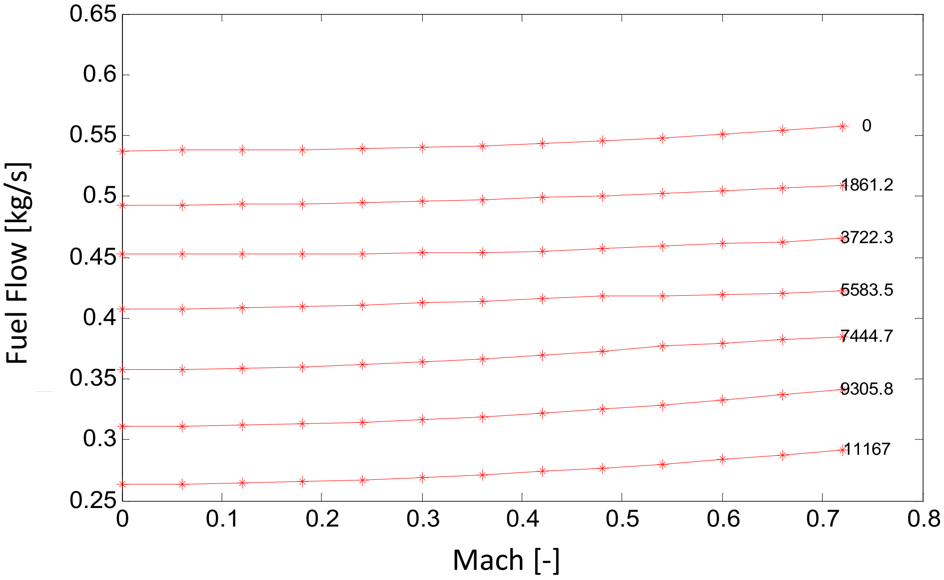

Figure 4-4 Fuel Flow [kg/s] over Mach for different altitudes [m]

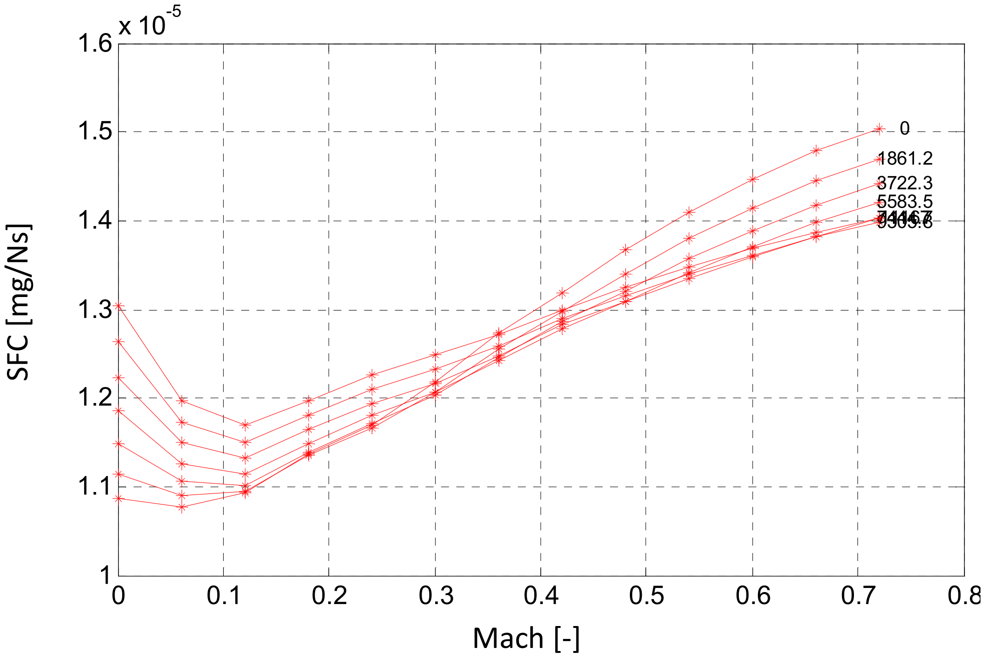

Figure 4-5 SFC [mg/Ns] over Mach for different altitudes [m]

The important increase in specific fuel consumption at ground level is due to the change in net thrust, for different Mach numbers. At altitude, the thrust is more constant so the increase in SFC is lower. This result is reasonable, because usually the lower fuel consumption over a mission profile is at altitude level at a fixed Mach number.

In the following figures, the total thrust F_N and the SFC in function of TET and Ambient Temperature deviation from ISA, at cruise Altitude and Mach conditions (9449 m and Mach 0.68).

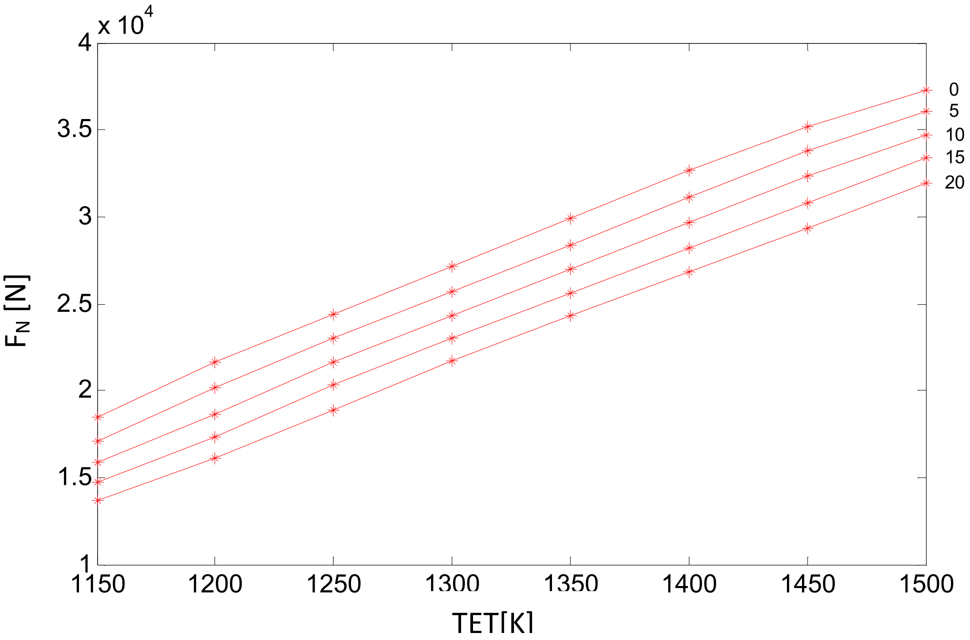

Figure 4-6 Thrust [N] over TET [K] for different ISA deviations [K]

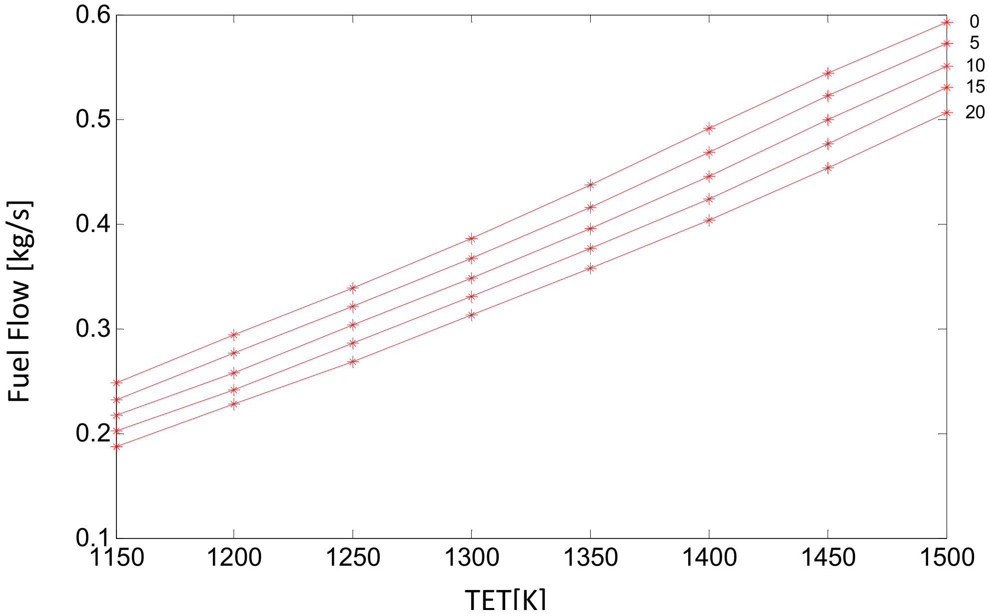

Figure 4-7 Fuel flow [kg/s] over TET [K] for different ISA deviations [K]

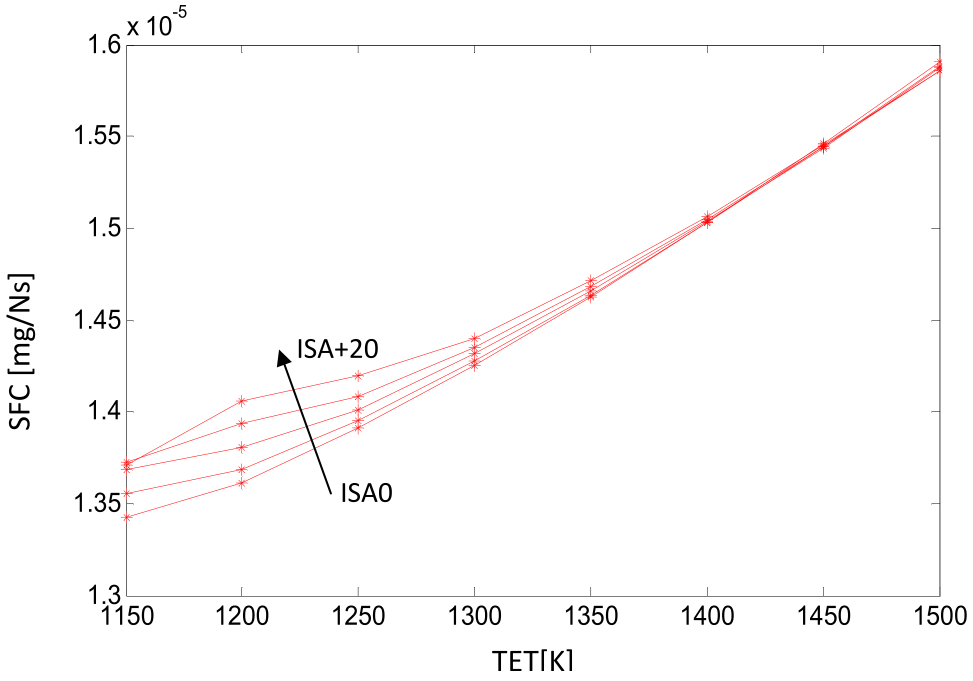

Figure 4-8 SFC [mg/Ns] over TET [K] for different ISA deviations [K]

The value of SFC increases with the TET. For low power settings, the SFC is lower at deviation zero from ISA than at deviation +20; this is due to the slightly difference in fuel flow change when the TET change.

All the results live up to expectations for this high performance turboprop engine.

4.4 Engine Rating

In order to assess aircraft performance, the engine model has to interact with the aircraft model. Therefore, it is important to understand the engine behaviour during the different flight phases, i.e. to find the power setting for each phase.

The thrust requirements are available in the public domain as ratio of the thrust to the take-off thrust for each phase [29]. For the aim of this thesis, the top of climb and take-off thrusts have been calculated from DP validation, matching the power output data. Then the TETs for each phase have been chosen in order to match the thrust requirements. The results are highlighted in the tables below.

Table 4-5 Engine rating TETs

Phase	**TET [K]**
Top-of-climb	1449
Take-off	1710
Approach	1105
Idle	985

Table 4-6 Engine rating thrusts

Parameter	**Rating**	**TPCU thrust [N]**	**Error**
Thrust top-of-climb	-	67504	-
Thrust take-off	-	76797	-
Thrust approach	$0.45*F_{N,TO}$	34839	0.81%
Thrust idle	$0.25*F_{N,TO}$	19334	0.75%

From literature [29], at the same flight conditions, the required thrust for cruise is supposed to be the 65% of the take-off value, while for climb is more likely to be around 85%. From DP validation, the top-of-climb value is the 88% of the take-off: this is because the literature data is the maximum power at cruise condition, which is likely to be at the beginning of the cruise, when the aircraft weight is higher. This point is also relates to the top of climb, so this temperature is a good rating for the climb phase.

The aircraft performance model requires only a maximum value of the TET for each phase and will then automatically calculate for the cruise segment a range of TET in order to reach the thrust required at every moment: therefore, this temperature can be used also as a maximum for the cruise phase.

To validate these results, it is important to understand the behaviour of the engine at different power setting. Usually, for normal turbofans, the highest shaft speed is at take-off because the TET is higher than for all other phases. Nevertheless, the ambient temperature is lower at altitude than at ground level, hence the non-dimensional speed and the ratio of the TET to the intake temperature are usually higher at top-of-climb than at take-off.

Looking to turboprop engines, they are usually installed on small aircraft, which fly at altitude below 8000 m, so much lower than common civilian turbofan aircraft. This operational condition may lead to the opposite situation and the highest value of the non-dimensional ratio is at take-off instead of at climb.

In the case of the TPCU model, the two values are very close: this result means that the power setting, combined with the ambient conditions, give similar rating for the two phases. In addition, the value of TET chosen for the take-off rating refers to the maximum achievable power output. This value, given in literature, allows the engine to support some critical A400M operations, such as short length runway and steep take-off. Consequently, a higher TET has to be chosen and the take-off point on the compressor maps may shift over the top-of-climb condition.

Plotting the compressor maps of the model and calculating the temperature ratios and the non-dimensional speeds, it has been possible to check this behaviour, as shown in the table below.

Table 4-7 Engine rating validation

Parameter	**Cruise value**	**Take-Off value**	**Climb value**
LPC CN	0.907	1.165	1.158
HPC CN	0.959	1.068	1.062
TET / T_{in_LPC}	4.604	5.830	5.852
TET / T_{in_HPC}	3.149	3.643	3.658

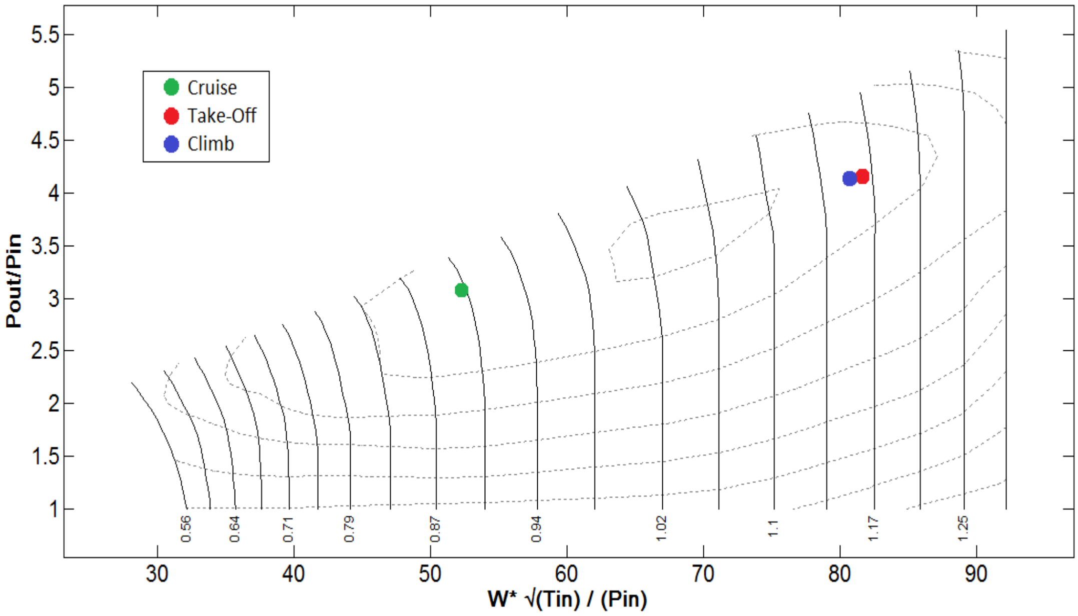

Figure 4-9 Operational points on LPC map[7]

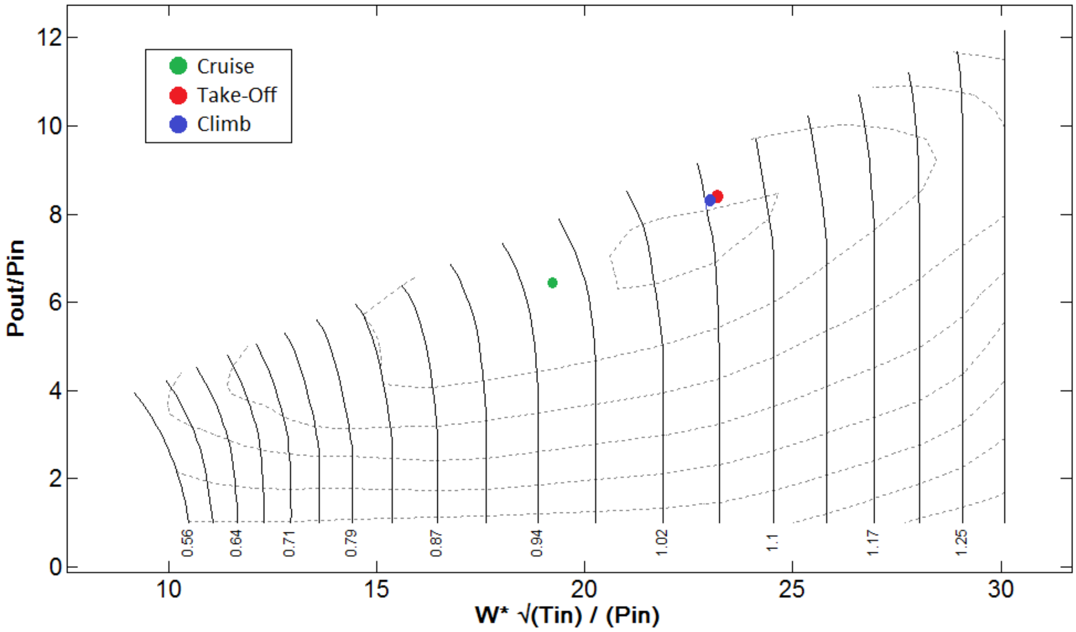

Figure 4-10 Operational points on HPC map

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[7] Units of the two compressor maps: the mass flow W is in kg/s, the temperature T is in K and the pressure p in atmosphere

Chapter 5 - AIRCRAFT PERFORMANCE MODEL

In this chapter, the overall structure and functioning of HERMES software have been highlighted, along with the main assumptions defined for the purpose of this thesis. In order to compare the A400M and the baseline performance, the fuel planning and the mission profile are the same for both the aircraft.

5.1 HERMES software

HERMES [30] is based on six modules, providing input data, mission profile data, atmospheric conditions and engine and aircraft performance calculations (see Appendix A). The modules calculate aircraft performance for climb, cruise, hold and descent segments; allowances are made for start-up, take-off, landing and taxi in and out.

All distances and times are unknown at the beginning, so an iterative procedure is performed in order to match the input mission range and fuel load (see Figure 5-1). First, the main mission range and the cruise time are guessed and a first iteration is made to match these two values. Afterwards, the same procedure is executed for the diversion mission (if needed). At the end, the hold, approach and landing phases and the fuel flow are calculated: the latter value, along with the payload, is subtracted from the MTOW to find a trial OEW. If this value doesn’t match the actual OEW of the aircraft, a new guess is made for the main mission range.

The initial guess for the cruise time is evaluated using the distance between the departure and the destination points and the cruise Mach number. The diversion mission is specified by the user in order to insure the correct amount of reserves. The contingency is the exact amount of fuel loads on board at the end of landing.

Cruise calculations are performed using the constant EAS, lift coefficient and SFC cruising method (see Appendix B.2). The stepped climb-cruise is evaluated by dividing the cruise segment in time intervals: the time spent at each segment is calculated in order to obtain the maximum specific fuel range. Then, the range equation is integrated numerically over the change in aircraft weight, in order to estimate fuel burnt and distance covered.

Climb and descent calculations are performed dividing the height into several intervals and using an iterative procedure for each of them. Time (function of height and speed), distance flown (function of speed and gradient), fuel burnt and aircraft weight are calculated at the end of each interval and they are then added to evaluate the total climb and descent values.

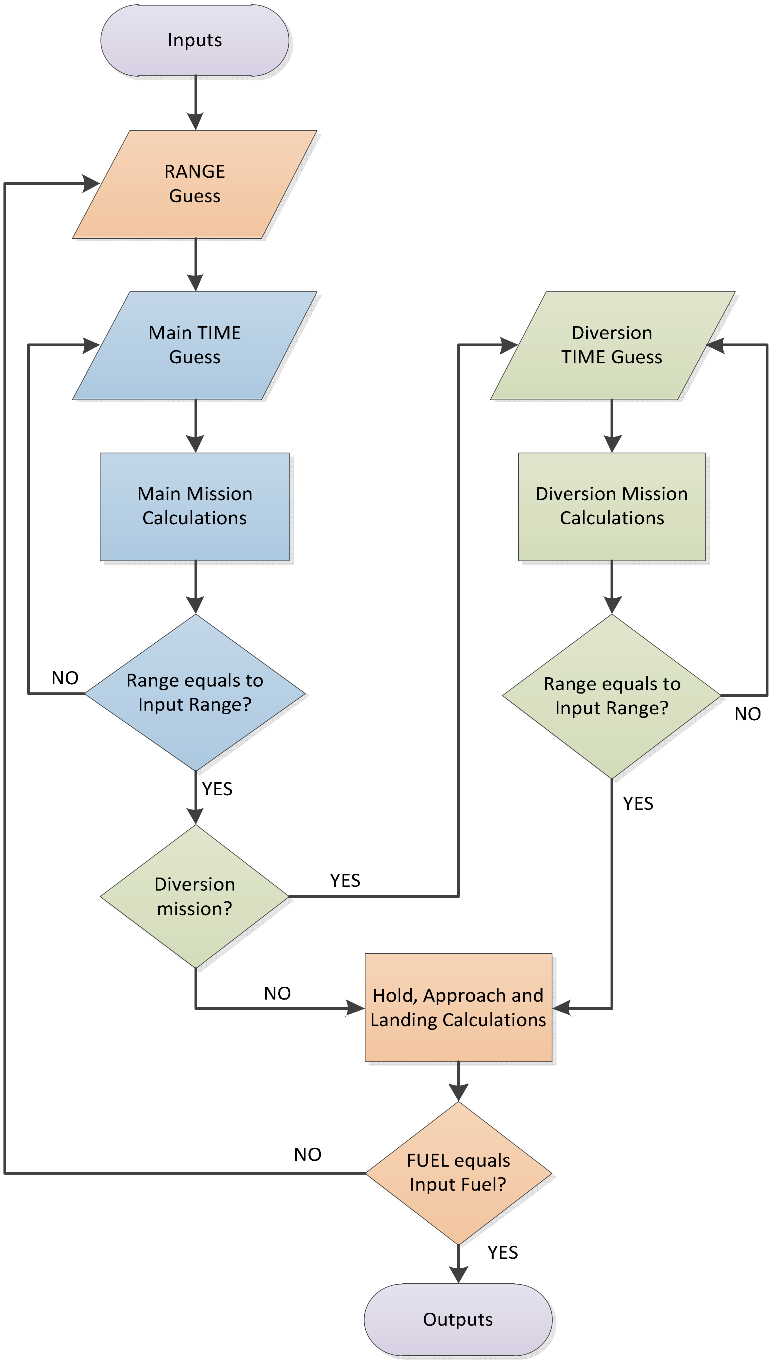

Figure 5-1 HERMES algorithm

5.2 Fuel planning and mission profile

The flight profile of the aircraft is divided in several segments, as shown in the Figure 5-2. The mission range is defined as the sum of the distances covered during climb, cruise and descent; the block range includes diversion, hold and landing.

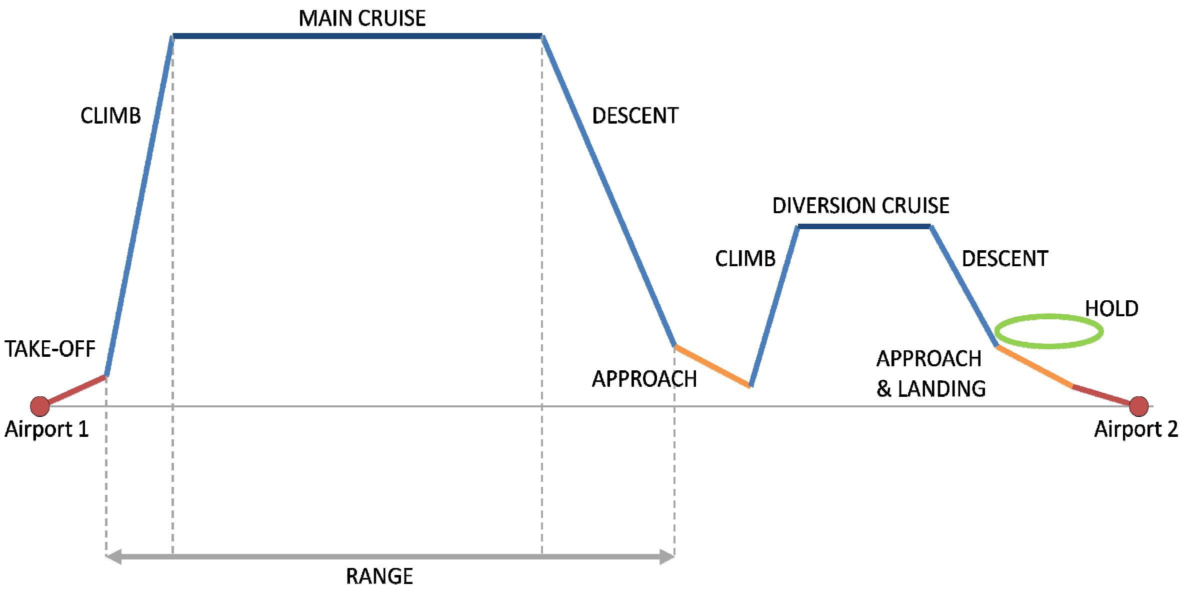

Figure 5-2 Mission definition

Several assumptions have been made in order to meet minimum standard of safety and operational requirements [30-32]:

- Only one cruise segment
- Climb to initial cruise altitude splits into three parts:
    - EAS is kept constant at 250 knots from 457m (1500ft) to 3048m (10000ft)
    - Acceleration to 320 knots at constant altitude
    - Climb to cruise altitude at constant EAS
- Zero wind
- Temperature deviation from ISA is constant for all segments
- Typical set of allowances and reserves defined to enable aircraft comparison and contingency fuel of 5% [33]
- Additional configurations neglected (i.e. bleeds)
- 100% power setting for all phases
- Mission type 2 (fuel calculation, for a defined range)

Table 5-1 Mission assumptions

Phase	**Parameter**	**Value**
TAXI	Time-in [min]	10
TAKE OFF	Time-in [min]	1
CLIMB	Initial altitude [m (ft)]	457.2 (1500)
	EAS range [knots]	250-320
CRUISE	Altitude [m]	A/C dependant
	Mach [-]	A/C dependant
DESCENT	TAS [m/s]	233-135
LANDING	Time [min]	6
	Runway Friction Coefficient [-]	0.02
	Runway Friction Coefficient with brakes-off [-]	0.3
DIVERSION	Altitude [m (ft)]	6096 (20000)
	Range [km (n.m.)]	370.4 (200)
	Mach [-]	0.65
HOLD[8]	Altitude [m (ft)]	457.2 (1500)
	Time [min]	30

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[8] The aircraft flies at condition of minimum fuel consumption and maximum endurance, i.e. maximum aerodynamic efficiency and minimum drag

Chapter 6 - ETRW SIMULATIONS AND RESULTS

The main objective of this thesis is the assessment of the ETRW performance of the A400M and the comparison with the chosen baseline. The aircraft model for the 737-800 is available on the Cranfield database [7; 34], while the A400M model has been built from literature data. The validation of the two models has been done using the available payload-range diagrams. Then, the ETRW parameter has been computed at condition of full load, from definition, and the comparison of the performance in report to the baseline has been discussed. A multi-objectives optimisation has been run in order to assess the effectiveness of the ETRW for aircraft performance measurement.

6.1 Methodology

In order to compare the performance of Airbus A400M with the chosen baseline, both the models need to be validated. The validation process is highlighted in the following path:

- The payload-range diagrams have been found in the public domain
- The maximum payload, maximum economic and ferry ranges have been calculated for the models
- The results have been compared with the literature values

With the aim of simulating the different conditions, the ranges have been found by matching the fuel weight available for each point, with the lowest possible error. For the maximum payload range, the fuel to match corresponds to the MTOW, minus the sum of the OEW and the MSP. In the second part of the diagram, the payload decreases in order to allow the fuel weight to increase, until the maximum fuel capacity is reached (i.e. the maximum economic range). Therefore, the condition to be matched is the MFC. To validate these results, the errors between the simulation values and the literature diagram have been calculated.

The second step has been to calculate the Energy Liberated to Revenue Work Ratio along the payload-range chart. The ETRW is defined in condition of maximum achievable payload for each range condition. Thus, only at full load it is possible to calculate the design value of the parameter for the chosen aircraft, along the payload-range diagram. After the simulations, the results for both the aircraft have been compared and discussed.

In addition, an interesting outcome of this thesis is the assessment of the relationship between minimum ETRW and maximum efficiency. A Genetic Algorithm Multi-objectives Optimisation has been run, obtaining the altitude-speed combination which gives the minimum ETRW and the maximum Specific Air Range, in order to check the existence of a unique solution for best efficiency.

6.2 Boeing 737-800 model validation

The overall data considered for the model of the 737-800 have been found in the public domain [7], as shown in the table below.

Table 6-1 737-800 overall data

Parameter	Value
MTOW [kg]	79016
MFC [kg]	20894
MSP [kg]	21319
OEW [kg]	41413
Cruise altitude [m (ft)]	10668 (35000)
Cruise Mach [-]	0.78

The model has been validated using the literature payload-range chart [7]. The weight errors have been found under the 0.5% while the range errors for maximum payload and maximum economic range payload are fewer than 2%. The overall results are collected in the table below.

Table 6-2 737-800 fuel weight matching

	Payload Weight [kg]	Fuel Weight [kg]	Weight Error
Max Payload Range	21319	16284	- 0.15%
Max Economic Range	16709	20894	- 0.55%
Ferry Range	0	20894	-0.29%

Table 6-3 737-800 payload-range validation

	Literature range [k n.m.]	Simulation range [k n.m.]	Range Error
Max Payload Range	2.00	2.03	- 1.5%
Max Economic Range	2.85	2.87	- 0.7%
Ferry Range	3.75	3.45	+ 8.0%

Considering the ferry range, the error is much higher than for all other conditions. This inaccuracy can be explained by looking at the aircraft operations. Usually, aircraft fly at Mach close to the optimum during the overall mission, in order to achieve the maximum possible Specific Air Range, but at ferry condition this optimum value cannot be achieved. However, the aircraft performance model employed doesn't take into account this change in Mach number during this phase, so that the result is wrong. Though, for the aim of this dissertation, this outcome doesn't affect the overall results: the ETRW increases sharply at ferry, by definition, so this part of the payload-range is not interesting and the model can be validated even with a higher error (see Figure 6-1).

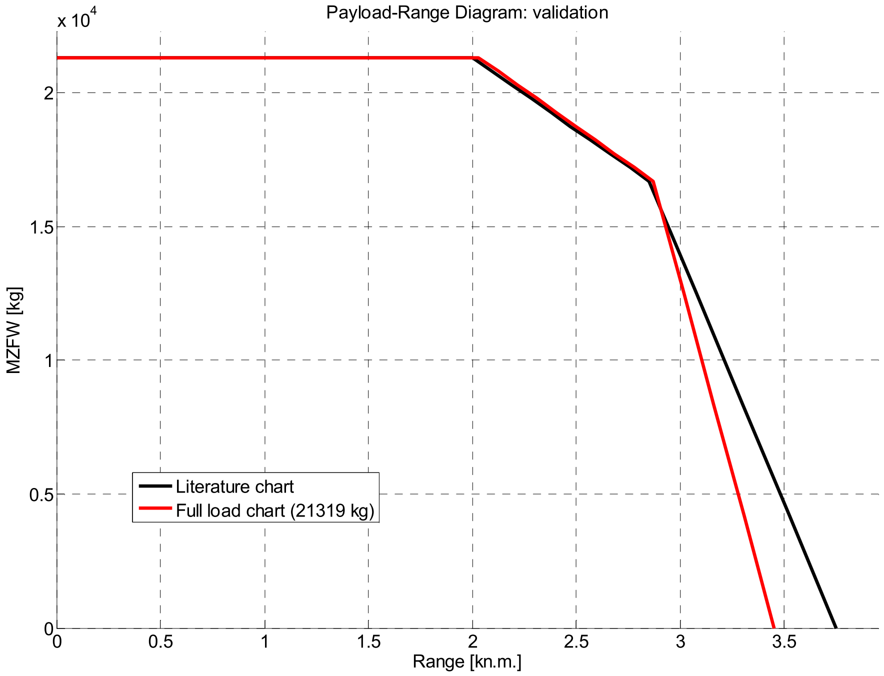

Figure 6-1 737-800 payload-range validation

6.3 Airbus A400M model validation

Also for Airbus A400M, the overall data considered for the model have been found in the public domain [13; 35; 36], as shown in the following table. However, in this case the data are not fully available, because the aircraft has been designed for military purpose and most of them are confidential.

Table 6-4 A400M overall data

Parameter	Value
MTOW [kg]	141000
MFC [kg]	50500
MSP [kg]	37000
OEW [kg]	78000[9]
Cruise altitude [m (ft)]	9449 (31000)
Cruise Mach [-]	0.68

The validation process has been undertaken by matching the model with the payload-range diagram available in literature [13]. In this case, the validation has been more complicated and the errors found are higher than for the 737-800 model. The weight errors are under 2%, but the consequently range errors are over 4%. It has not been possible to find a better solution, because a further decrease in the weight would have increased the range error.

Table 6-5 A400M fuel weight matching

	Payload Weight [kg]	Fuel Weight [kg]	Weight Error
Max Payload Range	37000	26000	+ 1.74%
Max Economic Range	12500	50500	- 0.36%
Ferry Range	0	50500	-1.47%

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[9] The OEW has been assumed in order to match with the payload-range diagram and the other data

Table 6-6 A400M payload-range validation

	Literature range [k n.m.]	Simulation range [k n.m.]	Range Error
Max Payload Range	1.78	1.68	- 4.2%
Max Economic Range	4.20	4.40	- 4.8%
Ferry Range	4.70	4.90	+ 5.7%

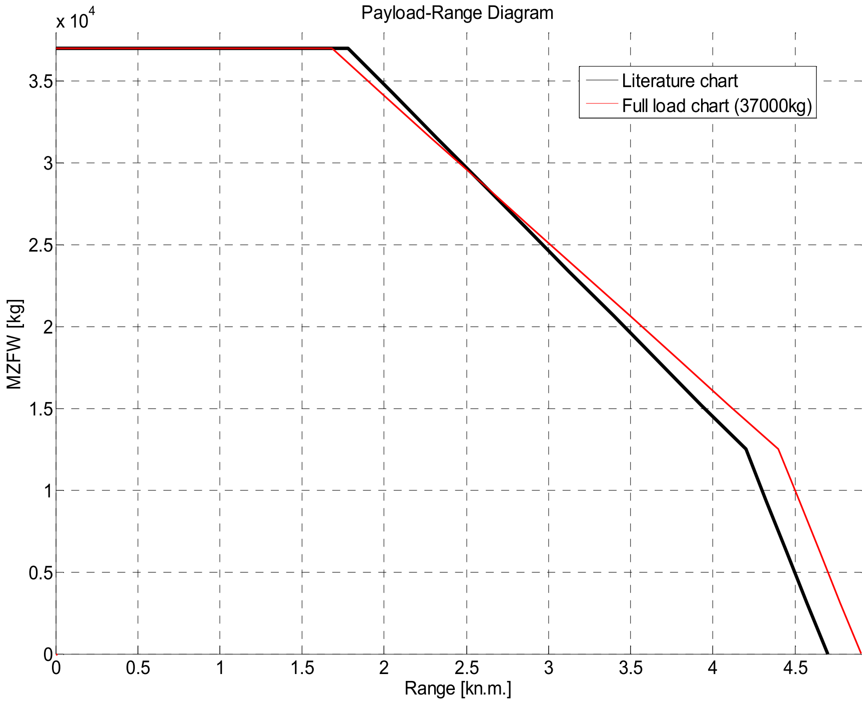

Figure 6-2 A400M payload-range validation

6.4 ETRW comparison and further discussion

As explained in the introduction of this thesis, Airbus A400M has been chosen in order to evaluate overall turboprop powered aircraft performance. Its design features, such as high wing configuration, thick walls and long tail, give very high drag and weight; therefore, they don't allow its use as a civilian passenger aircraft. With the aim of confirming these considerations, the ETRW parameter has been calculated at full load for both the A400M and the baseline.

As shown in the figure and table below, the A400M is less efficient than the civilian aircraft 737-800.

The exact difference has been evaluated only at maximum payload range condition, which is the point of maximum efficiency. Other assessments don't make any sense because the payload-range diagrams are too different. As a result, the ETRW at full load is the 8% higher for the A400M.

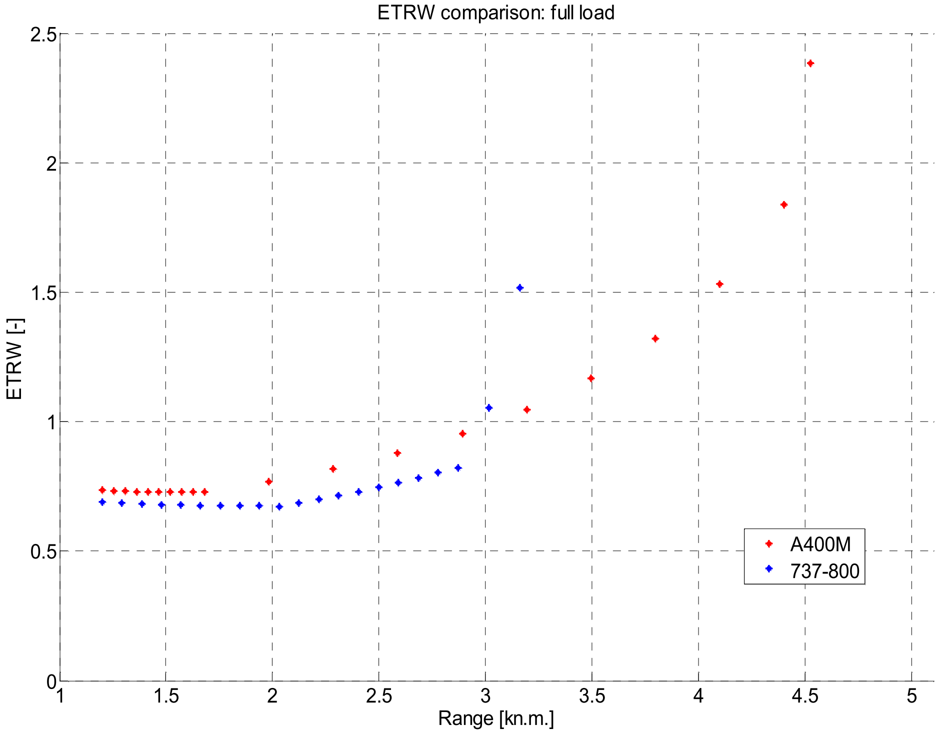

Figure 6-3 Full load ETRW comparison

Table 6-7 ETRW comparison at max payload range

Boeing 737-800 ETRW	A400M ETRW	Increase in ETRW
0.6739	0.7279	+ 8%

However, the substantial decrease in efficiency is mainly due to the applications and payload requirements of the A400M and not to the engine performance.

Some design and weight considerations have to be taken into account. The A400M is specifically designed for military cargo operations and high payload capabilities. The wings are installed on the top of the fuselage, in order to lodge the four turboprop engines far enough from the ground, avoiding problems during take-off and landing operations; this configuration increases consistently the overall drag of the plane. Besides, the landing gear is particularly heavy and the walls are very thick because they need to be reinforced, in order to carry important load. For these reasons, the overall weight of the aircraft is significantly high and the fuel needed to fly a certain range is surely higher for the A400M, decreasing the overall energy efficiency when compared with the baseline. As a result, the ETRW is at full load.

In the end, it is possible to infer that Airbus A400M is less energy efficient than a common civilian passenger airplane, even if it is the most advanced turboprop powered aircraft available in commerce. As explained above, this result is mainly due to the design aims of this aircraft and not to the turboprop characteristics. Therefore, a further study on the installation of the engines on a civilian aircraft body might lead to an interesting fuel efficient configuration for medium-long range aircraft.

Important to note, the potential of this kind of design are:

- In terms of the installation, the use of the engines on a ready-designed aircraft gives lowest development cost, because there is no need to start from scratch a new airplane concept and both the aircraft body and the engines successfully passed all security tests yet. In addition, the final solution is supposed to be high reliable, increasing the perception and acceptance of the new design by the costumers.
- In terms of fuel consumption, the advantages of the use of turboprop engines are remarkable. In particular, thinking about the possible market of this kind of configuration, it can have significant benefits in broad developing countries such as in the BRIC area, where the ticket price is one of the major passengers’ concerns and issues as noise and comfort are less critical.

6.5 Optimum altitude-Mach combination, for best ETRW and SAR

Aircraft performance changes when the aircraft flies at different altitudes and speeds. An optimum combination of these two parameters exists for maximum energy efficiency. In order to verify the effectiveness of the ETRW as efficiency metric, a unique solution has to be found for both the energy efficiency parameters, i.e. the ETRW and the SAR.

6.5.1 Methodology

Genetic algorithms are performed when a complete search of an optimum solution is impractical. They simulate the natural evolution, starting by a random population of possible solutions and generating new populations at any iteration, in order to reach a defined target. The new population is generated by the selection of the best solutions present in the old population and then performing a crossover procedure (or in other case a mutation). The best solutions are chosen using a fitness function and defining some targets (usually the minimisation of some parameters): when a solution satisfies the minimum criteria (or a maximum time/generations number is reached), the process terminates.

In the context of this thesis, a multi-objective optimisation has been performed, in order to find the altitude-Mach combination which gives the minimum ETRW and the maximum Specific Air Range (see Appendix B.2 for definition). Usually, the output of this kind of optimisation is a pareto-front, where no solution can be the best for all the target parameters, but every pareto solution is an optimum for the combination of the objectives.

The overall assumptions made in order to undertake the calculations are:

- Maximum payload range condition (knowing that the ETRW reaches the minimum at this particular range)
- The Mach number is evaluate from 0.68 (usual cruise value) to 0.72 (max engine operation value)
- The altitude is evaluated around the cruise value (9449 m)

The ETRW is calculated from its definition (equation (2-6) in chapter 2.1.1). The SAR fitness function is a combination of the equations (B-14) and (B-16) in Appendix B.2:

$$SAR = \frac{V}{Q_f} = \frac{TAS}{F_N * SFC} \qquad \textbf{(6-1)}$$

Where V is the true air speed, Q_f the fuel flow, F_N the net thrust and SFC the specific fuel consumption of the four engines.

Net thrust and SFC are computed from HERMES simulations; the true air speed is calculated from:

$$TAS = M\, a_0 \sqrt{\frac{T}{T_0}} \tag{6-2}$$

Where flying M is the Mach number, a_0 the speed of sound at SLS condition, T the altitude temperature and T_0 the reference temperature (ISA SLS). The value of the altitude temperature is computed by interpolation from literature data [38].

6.5.2 Optimisation results and discussion

After optimisation, it has been possible to confirm that only one optimum solution exists, in order to minimise the ETRW and maximise the SAR. The optimisation converges around two different combinations of altitude and Mach, as shown in the table below. However, the difference between the values is very low, with errors under the 0.5%, so that it is possible to assume that the solution is unique.

Table 6-8 Optimisation outputs

	Mach [-]	Altitude [m]	SAR [-]	ETRW [-]
Output 1	0.718	9063	0.1737	0.7059
Output 2	0.716	9092	0.1735	0.7054
Error	-0.2%	+0.3%	-0.1%	-0.07%

It can be observed that the value of Mach number is very high for a turboprop (very close to the maximum achievable Mach of the real engine). Some considerations have to be made:

- The upper limit of the Mach number range refers to the operational condition of the engine, but the model is not limited to this value. Thus, running simulations above this number, another optimum can be found, but the result cannot be trusted.

Therefore, in order to ensure that the actual optimum is an acceptable result, a validation process has been undertaken (see Appendix D)

- The value of Mach is close to the maximum cruise value, but it is not equal. However, both the software and the overall procedure can be affected by small approximation errors. Consequently, the actual optimum is likely to move even closer to the maximum Mach
- The optimisation has been run at maximum payload-range condition, the most efficient point of aircraft operations: hence, the high value of Mach means that the plane is fast enough to cover the range with the smallest possible fuel and without time losses

In order to verify the results, the fuel burnt MMF (which influences linearly the ETRW) and the SAR have been calculated at the condition of optimum altitude, for a certain range of Mach number (i.e. 0.66 – 0.72). In the figures below, it is possible to see how the first parameter reaches the minimum at maximum speed, while the second parameter achieves its maximum. This result confirms the effectiveness of the ETRW as a metric for energy efficiency.

A further observation has to be made, as explained before: the trend of the two parameters is monotonic and the optimum is close to the upper limit. Hence, it is possible that a maximum/minimum would be found for a highest value of Mach number, but the operative conditions of the engine don’t allow an increase of the speed. Consequently, the existence of an extrema cannot be checked in these conditions, but it has to be checked over a larger Mach number range. This scheme has been followed in the validation process and the results have been confirmed (see Appendix D).

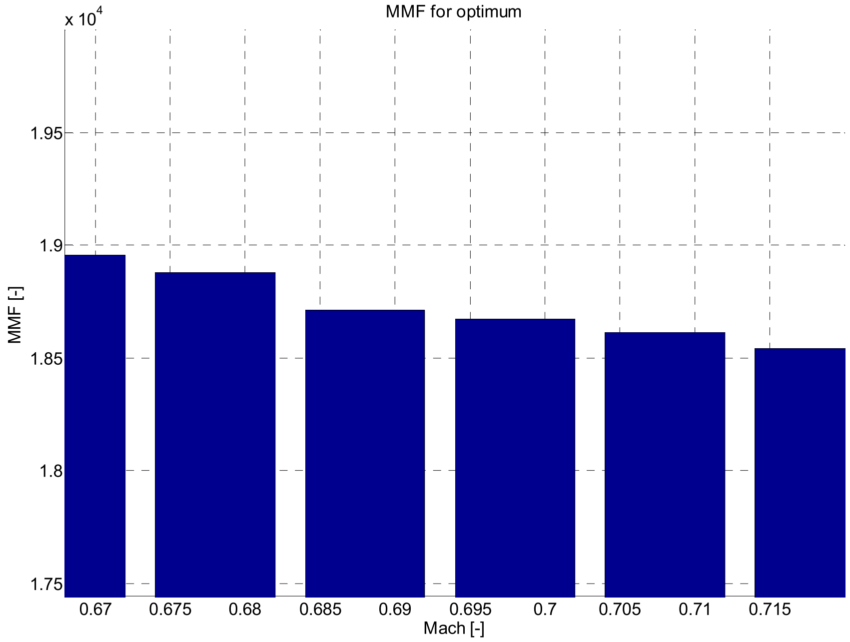

Figure 6-4 MMF over Mach, at optimum altitude

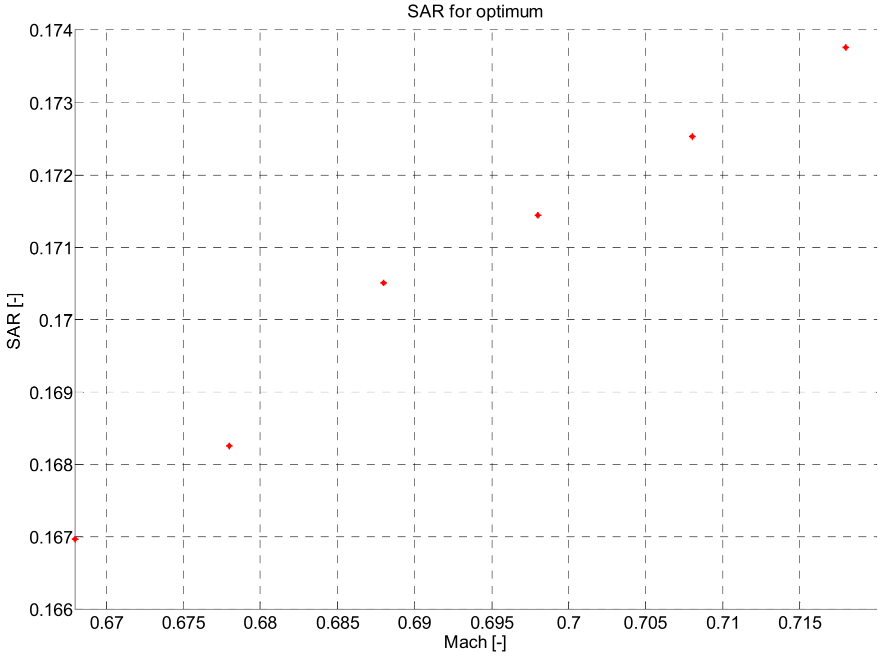

Figure 6-5 SAR over Mach, at optimum altitude

Chapter 7 - LOAD FACTOR SENSITIVITY ANAYSIS

Nowadays, commercial aircraft are unlikely to fly at full load, even when they reach the maximum number of passengers. Consequently, the operational energy efficiency of the mission decreases. In order to assess this reduction and compare the performance of the A400M and the baseline, a sensitivity analysis of the effect of the load factor decrease has been undertaken in this chapter.

7.1 Boeing 737-800 part load performance

The influence of the Load Factor over the reduction in energy efficiency has been presented in chapter 3.3.1. Some interesting values of the LF have to be chosen, in order to assess the reduction of the ETRW parameter and compare the performance of the two aircraft.

The two conditions chosen for Boeing 737-800 are 90% and 69% of the full load (see Table 7-1). The second value is particularly interesting because it is the payload which is carried in case of only passengers and luggage, in the two-class configuration, with no additional cargo (taking an average weight of 90.7 kg per passenger, personal luggage included, for 162 passengers).

The payload-range diagram has been re-calculated in these new conditions, as shown in the Figure 7-1. For these new payload-range conditions, the ETRW has been evaluated, as shown in the Figure 7-2. As expected, the value is higher for the part load flights, increasing by the 35% for a Load Factor of 0.69, at maximum payload range. These results confirm the thought that current aircraft fly usually in a very inefficient way. Therefore, an important improvement in aircraft operation for the short term might be to increase the overall Load Factor, by increasing par example the freight-belly cargo.

Table 7-1 737-800 part load factors

Payload [kg]	LF = Payload / MSP	Range [k n.m.]
21319	1.00	2.03
19108	0.90	2.43
14696	0.69	2.94

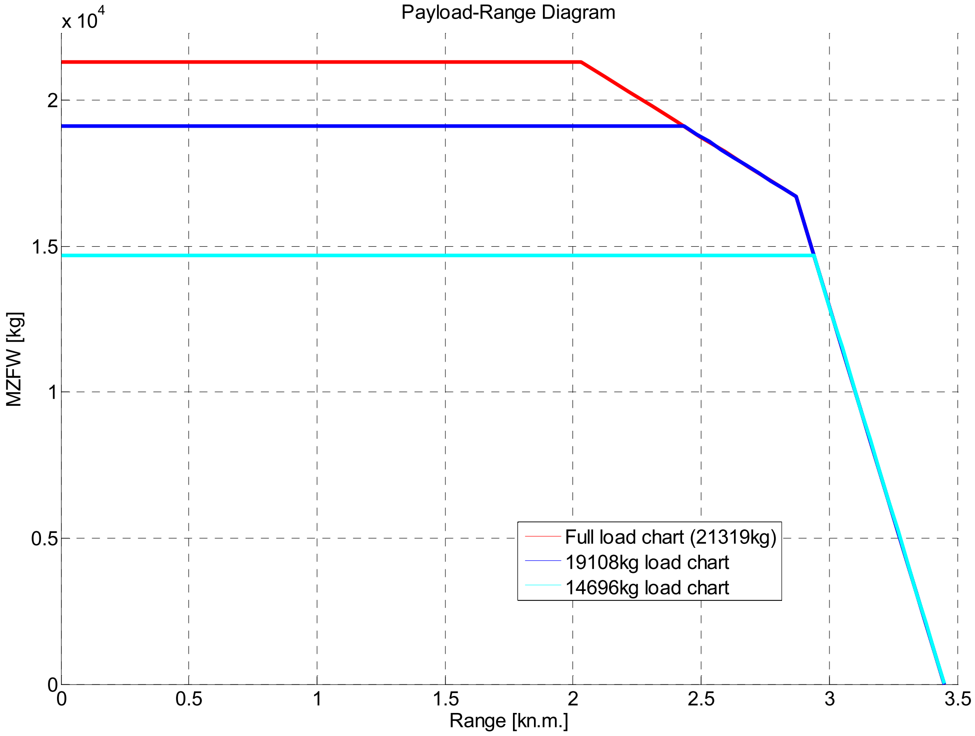

Figure 7-1 737-800 part load payload-range charts

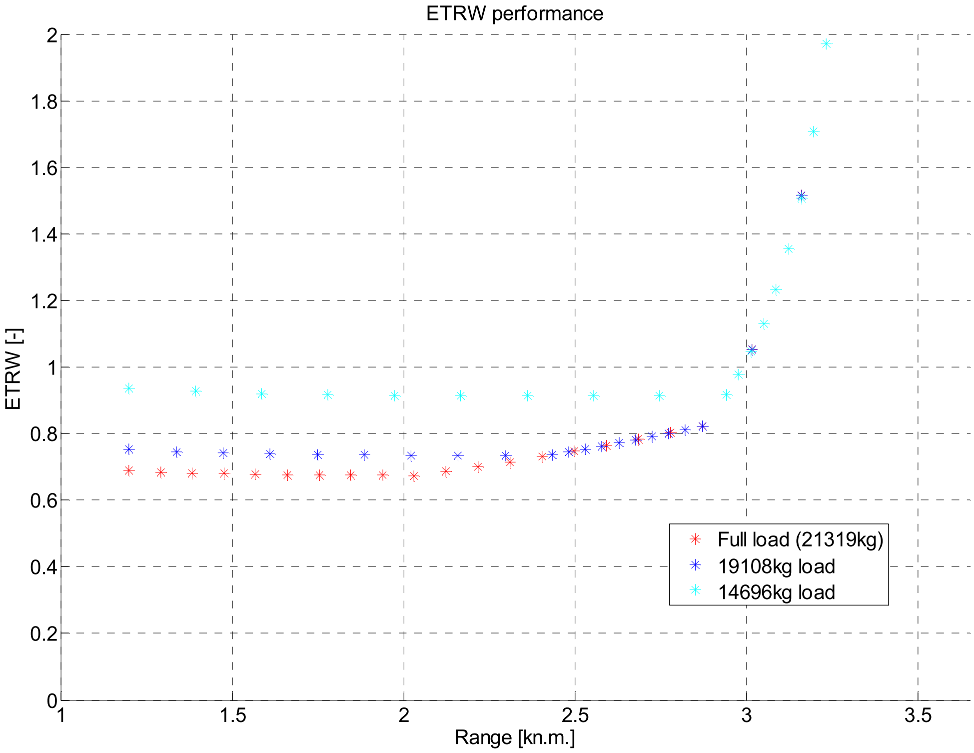

Figure 7-2 737-800 part load ETRW

7.1 Airbus A400M part load performance

For the Airbus A400M, the load factors have been chosen at 60% and 40% of the full load. The first value is the average LF of worldwide aircraft fleet found during the literature review (see chapter 3.4). The second value is the same amount of payload of the baseline for only passengers and luggage. The choice of this value has been made in order to compare the performance of the two aircraft while they carry the same payload, having assumed that they are able to carry the same number of passengers. The values of the LFs, the payload-range diagrams for the two cases and the values of the ETRW are shown in the table and figures below.

Table 7-2 A400M part load factors

Payload [kg]	LF = Payload / MSP	Range [k n.m.]
37000	1.00	1.68
22200	0.60	3.25
14696	0.40	4.10

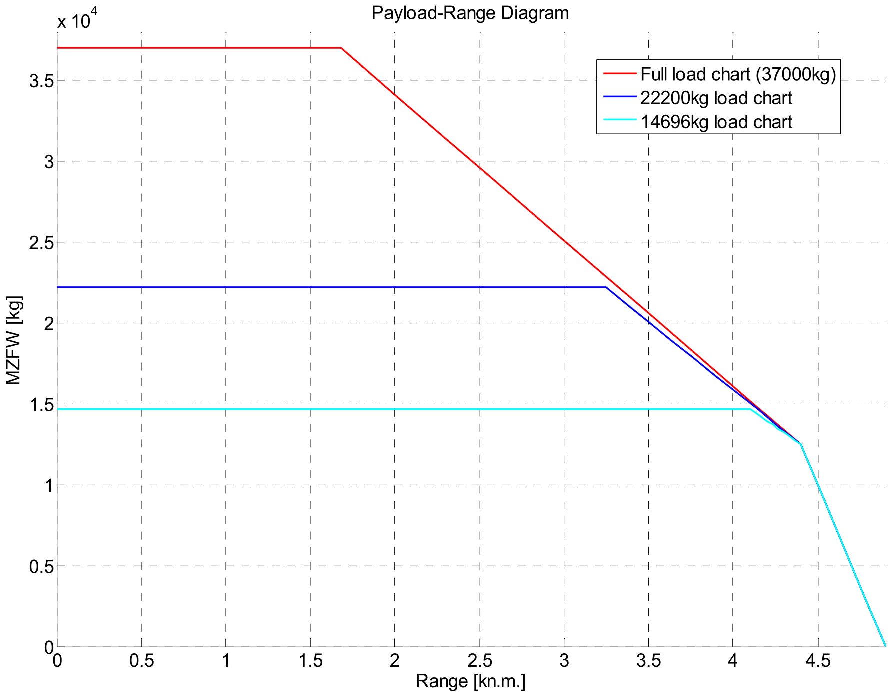

Figure 7-3 A400M part load payload-range charts

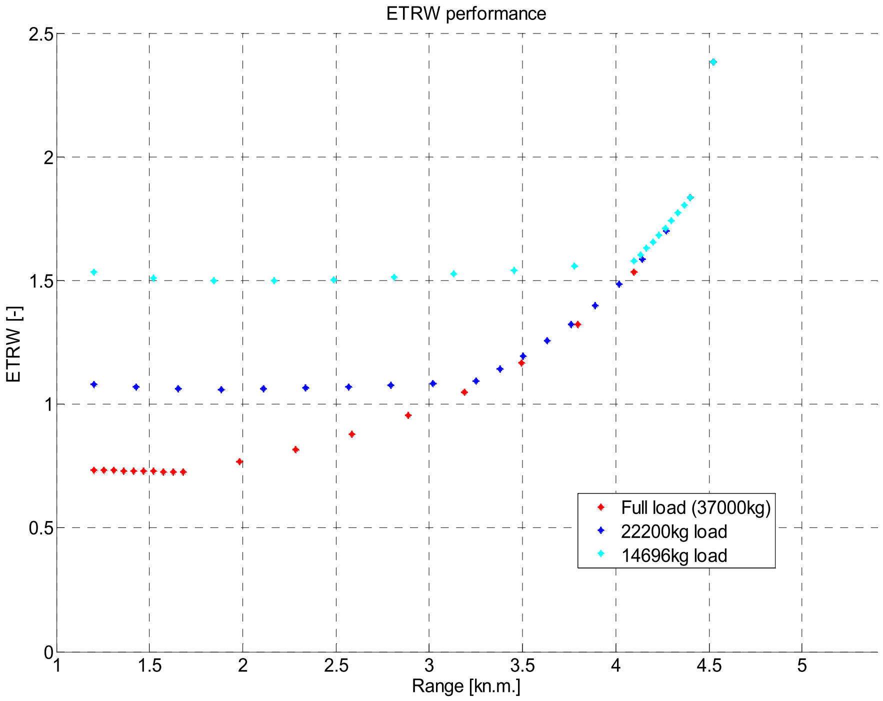

Figure 7-4 A400M part load ETRW

As expected, also in this case the ETRW is much higher at part load: it even doubles its value while flying at a Load Factor of 0.4, increasing of the 98% at maximum payload range. Further considerations on the reason of this important decrease in the energy efficiency while compared with the baseline will be highlighted in the following section.

7.2 Comparison and further discussion

As it can be seen in the table and picture below, the ETRW at full load is the 8% higher for the A400M, while at part load the increase is much more important (more than double).

Table 7-3 ETRW comparison at max payload range

	Boeing 737-800 ETRW	A400M ETRW	Increase in ETRW
Full load	0.6739	0.7279	+8%
Part load	0.9127 (LF 0.69)	1.4993 (LF 0.40)	+64%

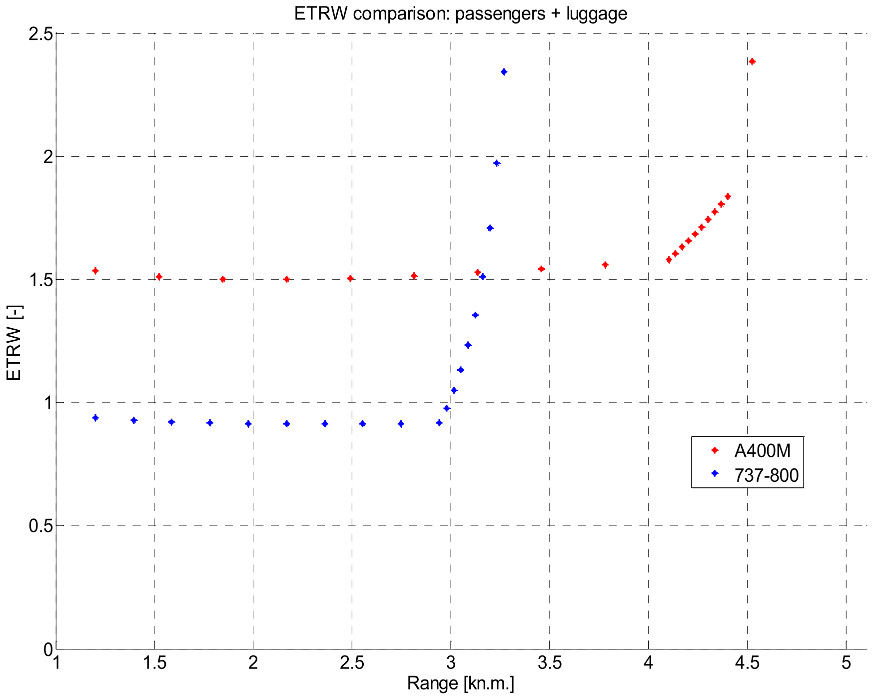

Figure 7-5 PL = 14696 kg, ETRW comparison

This substantial decrease in efficiency is mainly due to the Load Factor effect: for the same amount of payload, the LF for the A400M is quite half of the value for the baseline (LF = 0.4 against 0.69). As explained in the chapter 3.3.1, the sensitivity of the ETRW on the payload carried is very high, so that a slightly change in the LF gives a significant decrease in the energy efficiency, for the same range condition. For this reason, the aircraft looks much less efficient than the baseline, in condition of only passengers and luggage. This consideration confirms the non-suitability of the A400M for medium range civilian operations.

Chapter 8 - ENGINE DEGRADATION SENSITIVITY ANALYSIS

During the aircraft life, the engine inevitably degrades and the overall fuel consumption increases. Consequently, the ETRW parameter changes: a sensitivity analysis of the effects of components efficiency and mass flow degradation has been undertaken in this chapter. The engine has been rated in order to obtain the same amount of thrust of the clean engine (so higher TET). Then, the decrease in payload needed to achieve the same maximum payload and maximum economic ranges has been evaluated. Finally, the reduction in energy efficiency for each degradation case has been quantified and discussed.

8.1 Degraded engine rating and methodology

In order to assess the behaviour of the ETRW during the aircraft life, a sensitivity analysis has been done about the effects of engine degradation on the aircraft energy efficiency.

The methodology which has been followed is:

- The degradation modes have been chosen in order to compare clean engine performance with difference degrees of degradation
- The engine has been rated for each degradation mode, in order to achieve the same thrust levels of the clean engine
- The payload-range chart has been re-calculated, in order to find the decrease in the amount of payload to be carried to fly the same maximum payload and maximum economic ranges
- The change in ETRW has been finally assessed and discussed

As first step, the calculation of the engine rating for the degradation modes has been produced. The results are shown in the tables below.

The degradation factors have been chosen by taking some average data from literature [37], regarding compressor’s mass flow and efficiency and turbine’s efficiency degradation.

Table 8-1 Degradation factors

	Compressor mass flow degradation	Compressor efficiency degradation	Turbine efficiency degradation
Clean Engine	1.0	1.0	1.0
Degradation mode1	0.970	0.990	0.995
Degradation mode2	0.950	0.980	0.990
Degradation mode3	0.930	0.970	0.985

The engine rating has been found by increasing the TETs for each phase, in order to obtain the same levels of thrust of the clean engine. The TETs and the errors found are shown in the following tables.

Table 8-2 Rated TETs

Phase	Clean TET [K]	Degradation mode1 TET [K]	Degradation mode2 TET [K]	Degradation mode3 TET [K]
Top-of-climb	1449	1474	1489	1509
Take-off	1710	1710	1710	1710
Approach	1105	1110	1125	1140
Idle	985	990	1000	1011

Table 8-3 Rated thrust errors

Phase	Clean Thrust [N]	Degradation mode1 Error	Degradation mode2 Error	Degradation mode3 Error
Top-of-climb	67504	+0.42%	- 0.41%	- 0.73%
Take-off	76797	- 0.05%	- 0.34%	- 0.92%
Approach	34839	- 0.45%	+0.09%	+0.54%
Idle	19334	- 0.27%	- 0.78%	- 0.89%

The engine has been rated for each mode with very low errors; consequently, the results have been validated.

A peculiarity of the model is that the take-off thrust decreases of around 1% from the clean mode to the last degradation mode, even if the TET is quite constant. The diminution on thrust will affect aircraft operations, by increasing the runway field length at take-off. This behaviour has been verified during the aircraft performance assessment and effectively the runway increases of around 200 m. Thus, the results for take-off TETs can be validate. However, an important consideration has to be made: in these new conditions, the airplane may be not able to take-off from airports which have a short runway, affecting aircraft operations.

8.2 Degradation results and discussion

In order to insure all usual operations, the aircraft has to be able to fly the same maximum payload and maximum economic ranges even with a degraded engine. However, when degradation occurs, the fuel consumption increases. Consequently, if the plane tries to achieve par example the maximum payload range at full load, it will require higher amount of fuel so that it will exceed the MTOW. In order to achieve this range, the payload carried has to decrease of the same amount of extra-fuel needed.

In the figure and table below, it is possible to see the reduction of payload for each degradation mode, for both the ranges.

Table 8-4 Payload reduction and errors

	Max Payload [kg]	**PL / MSP**	**Max Economic payload [kg]**	**PL / MSP**
Clean Engine	37000	-	12500	-
Degradation mode1	36200	- 2.2%	11000	- 12%
Degradation mode2	35700	- 3.5%	8000	- 36%
Degradation mode3	35500	- 4.1%	6500	- 48%

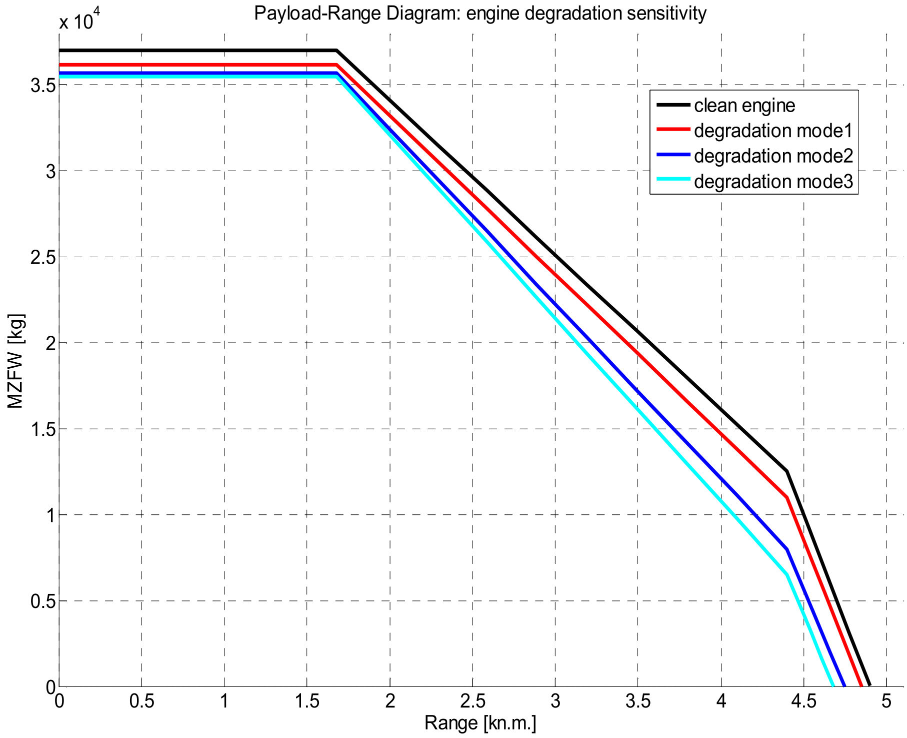

Figure 8-1Payload-range variation

The decrease in payload for the first range is quite small, so the airplane will still be able to fly the maximum payload range with a load factor higher than 95%. For the second range, the situation is quite different: the reduction in payload is significant, so the airplane will not be able to cover the all range if the degradation is important, without decrease considerably the payload carried. Therefore, in this particular condition it is necessary to ensure engine components washing in order to restore the efficiencies.

Further considerations have to be made on the ferry range, which decreases substantially along with engine degradation, as shown in the table below. This reduction is again because of the extra-fuel to be carried on the plane, which limits the maximum range achievable.

Table 8-5 Ferry range variation

	Ferry range [k n.m.]	**Error**
Clean Engine	4.90	-
Degradation mode1	4.85	- 1.0%
Degradation mode2	4.75	- 3.1%
Degradation mode3	4.68	- 4.5%

The main step of the engine degradation sensitivity analysis on the aircraft performance is the evaluation of the change in ETRW. In the figure and table below, the results for clean and degraded engine have been highlighted.

Table 8-6 ETRW sensitivity errors

	Max Payload ETRW	Error	Max Economic ETRW	Error
Clean Engine	0.7279	-	1.8376	-
Degradation mode1	0.7500	+3.1%	2.0906	+13%
Degradation mode2	0.7726	+6.1%	2.8529	+55%
Degradation mode3	0.7897	+8.5%	3.5271	+92%

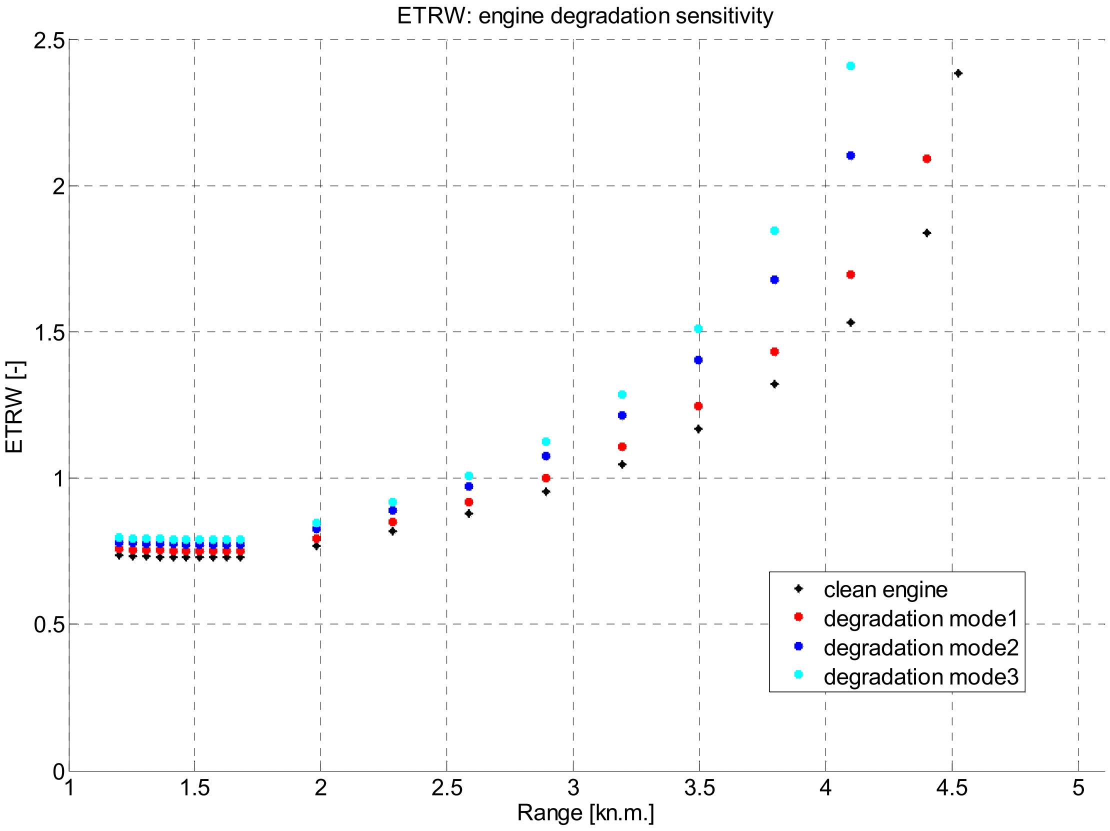

Figure 8-2 ETRW sensitivity to degradation

The overall results show an increase of the energy efficiency parameter, because of the increase in fuel consumption and the simultaneous decrease in payload carried, as expected. This phenomenon is much higher when the aircraft flies over its maximum payload range, because of the more important decrease of payload. In particular for the last degradation mode, for a decrease of payload of around 50%, the ETRW parameter doubles its value.

In conclusion, it is important to point out how the energy efficiency of an aircraft changes over its payload-range in order to fly the same trajectories:

- Until the maximum payload range has been reached, the ETRW increases but not too importantly (at least for the first two degradation modes). The plane can still fly the same distances with a quite high load factor and its operations are not compromised
- For all other ranges, the increase in ETRW becomes significant, along with the decrease of payload carried. For small degradation factors, the aircraft will still be able to achieve satisfactory performance, but for higher values the efficiencies of engine components may have to be recovered in order to maintain high performance

As a result of the above considerations, it is possible to infer that the ETRW parameter can be employed as an indicator of engine degradation. As a further work, it can be interesting to develop a model/tool based on the ETRW calculation, in order to check the overall level of degradation of the engine. This tool can be useful for the operator in order to know when undertake more accurate diagnostics on the engine, saving time and money. The idea is to simply check the fuel burnt for a given mission and to evaluate the change in ETRW, to use it as an input of the engine degradation assessment tool.

Chapter 9 - ENVIRONMENTAL IMPACT ESTIMATION

Aircraft emissions depend mainly on the amount of fuel burnt during a mission and the characteristics of the propulsive system. For this reason, the ETRW parameter can be exploited for aviation environmental impact assessment, in order to calculate the Coefficient of Environmental Performance. In this chapter, carbon dioxide and water vapour emissions have been evaluated using the Fuel Composition Method. The NO_x has not been taken into account, because of a lack of literature data on turboprop emissions performance.

9.1 Introduction

Current aviation concerns apply mainly to carbon dioxide, nitrogen oxides and water vapour.

The carbon dioxide is one of the dominant anthropogenic greenhouse gases, the 73% being produced from fossil fuels (2% used for civil aviation). It contributes to the global warming, altering the balance of incoming and outgoing radiation from the Earth surface; it stays in the atmosphere for longer than a thousand years and CO_2 emissions have the same value regardless the altitude.

NO_x is responsible of ozone formation at ground level and of its depletion at altitude, being hazardous to the human health and contributing to the ozone hole formation in the stratosphere. Its effect is particularly important at high power setting, so that turbofan engines are more concerned that turboprops, having usually higher TETs.

Water vapour formation has an important greenhouse effect, because in cold environments the vapour condenses into droplets and creates contrails. They are responsible for high altitude cirrus clouds formation, with a strong impact on global warming effect. However, they normally do not form at lower altitude (usually below 8000m/26000ft): turboprop engine are commonly employed on low cruise altitude aircraft, consequently water emissions are less important for these airplanes.

An objective of this thesis is the investigation of the possibility to exploit the ETRW parameter for aircraft emissions assessment. As shown in equation (3-2) of chapter 3.1, it is possible to evaluate the Coefficient of Environmental Performance as the amount of emissions released per unit of revenue work performed, dependant on the ETRW, which is in turn dependent on the amount of fuel burnt and on the aircraft capabilities in terms of payload and range.

For this purpose, CO_2 and water vapour emissions have been evaluated by performing the Fuel Composition Method [39].

On the other hand, NO_x emissions have not been considered: the emissions model is based on the Stirred-Reactor Method [40; 41], which is much more complex than for the other pollutants. In particular, in order to find the parameters which drive the combustion, the model needs a validation process, but it cannot be undertaken because literature data for turboprop engines are not available.

9.2 Fuel Composition Method

The CO_2 and the water vapour are natural products of fuel oxidation and their quantities depend on the elemental composition of the fuel chosen.

Assuming complete combustion[10] and knowing that the fuel composition can be represented as $C_mH_nS_r$, this method considers the Carbon, Hydrogen and Sulphur coefficients m, n and r in order to evaluate the amount of CO_2 and water vapour emissions in grams par kilograms of fuel burn.

The Emissions Index of CO_2 and H_2O are:

$$EICO_2\,[g/kg] = \frac{1000\,m\,(12.011 + 2 * 15.9994)}{m\,12.011 +\, n\,1.0079 +\, r\,32.06} \tag{9-1}$$

$$EIH_2O[g/kg] = \frac{1000\frac{n}{2}\,(2 * 1.0079 + 15.9994)}{m\,12.011 +\, n\,1.0079 +\, r\,32.06} \tag{9-2}$$

Thus, assuming the chemical composition of kerosene as $C_{12}H_{26}$, it is possible to calculate the EI for the two pollutants, for aviation engines; the results are:

- $EICO_2$ = 3100.4 g/kg
- EIH_2O = 1374.9 g/kg

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[10] In order to calculate CO_2 emissions, the error related to this assumption is negligible because modern engines are very efficient in oxidize the fuel burn. Thus, the mass of CO_2 emitted during a mission is significantly greater than CO, HC or NO_x emissions.

It is important to mention that the above values are constant for all flight phases; consequently they don't change during the mission.

To compute the overall mission emissions, it is then sufficient to multiply the EI by the whole amount of fuel burnt in kg:

$$E_{CO_2}\,[g] = EICO_2 * fuel\_burn \tag{9-3}$$

$$E_{H_2O}\,[g] = EIH_2O * fuel\_burn \tag{9-4}$$

9.3 Results and further discussion

The amount of CO_2 and water vapour emissions in kg has been calculated for the two aircraft, the A400M and the baseline, over their own payload-range charts. The gross value relates directly to the total fuel burnt during each mission range, as shown in the figure below.

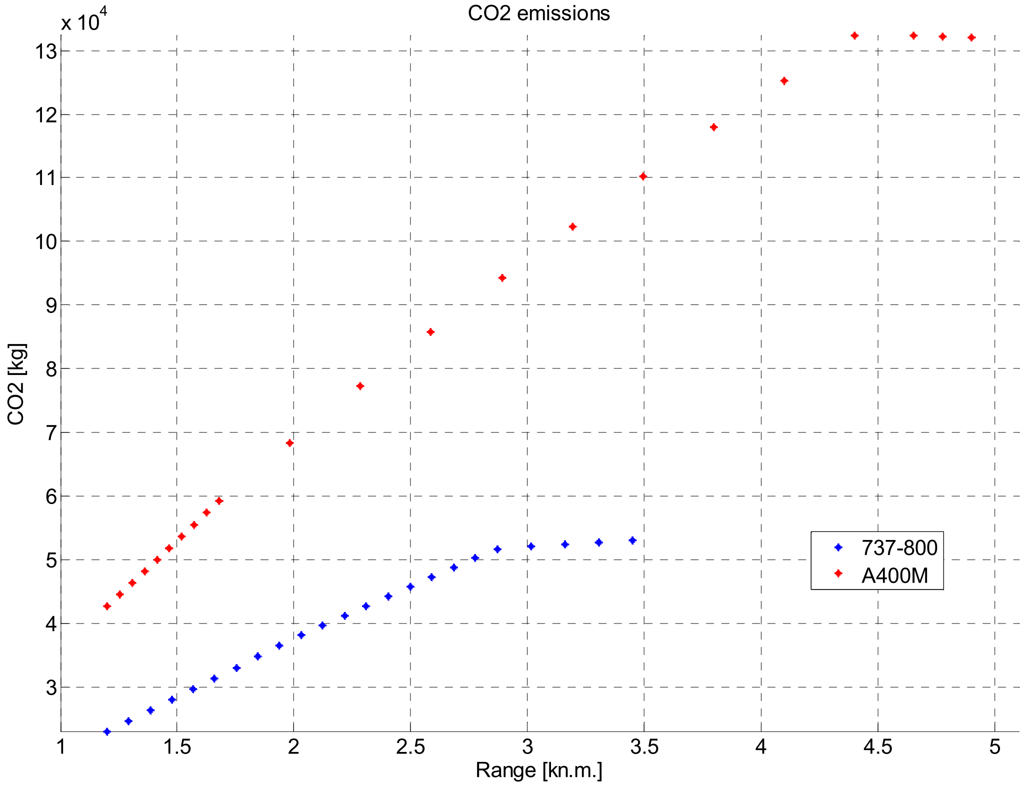

Figure 9-1 Gross CO_2 emissions over payload-range chart

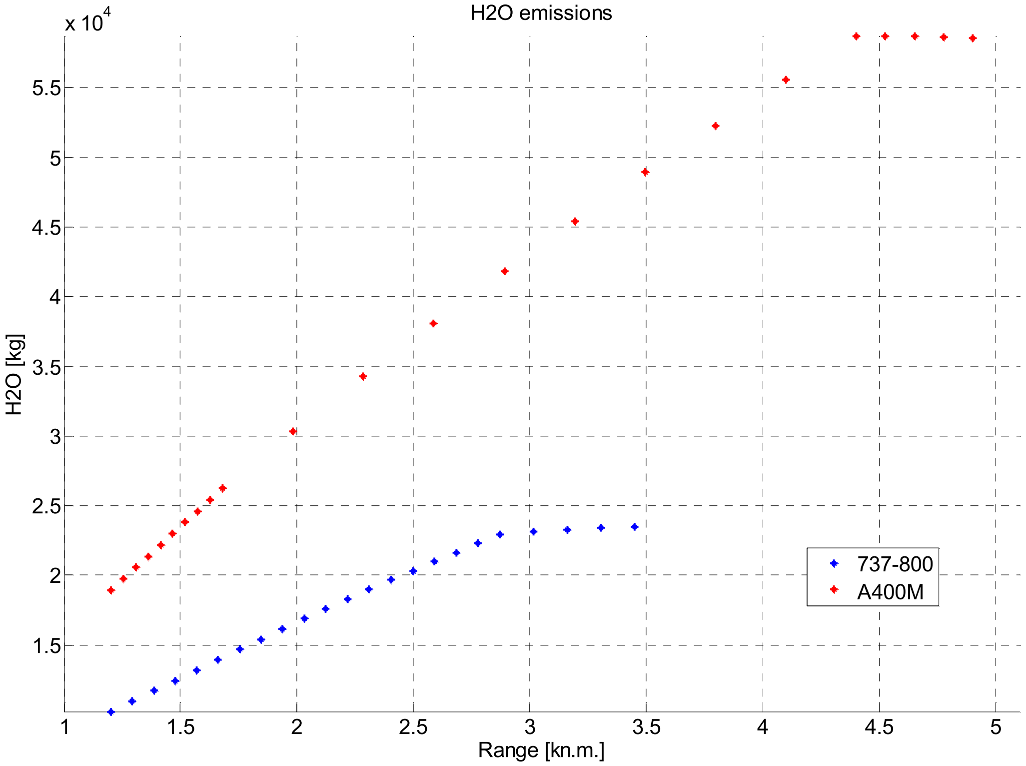

Figure 9-2 Gross H_2O emissions over payload-range chart

The gross amount of emissions for the A400M is much higher because the dry weight of the aircraft is twice the weight of the baseline. Consequently, for the same range flown, the A400M needs much more fuel in order to complete the mission. As CO_2 and water vapour emissions depend directly on the fuel burn, the total amount of pollutants produced is substantially higher for the A400M, when compared to the civilian aircraft.

Nevertheless, the above consideration doesn't mean that the environmental performance of the A400M is significantly lower than the baseline. The overall performance depends not only on the absolute value of fuel consumed, but it is important to take into account aircraft dimensions and capabilities and fuel energy efficiency, in order to compare the aircraft on the same conditions. For this reason, the ETRW parameter can be employed in conjunction with the pollutant emissions indices, in order to evaluate the Coefficient of Environmental Performance.

Therefore, the assessment of aircraft effects on the environment by computing the CEP is simple, comprehensive and reliable.

In the Figure 9-3, the parameter has been calculated for both the aircraft by taking into account CO_2 and water vapour emissions, as shown in the following equation (simplified form of the equation (3-2)):

$$CEP = ETRW * \sum (EI_{CO_2} + EI_{H_2O})^{11} \tag{9-5}$$

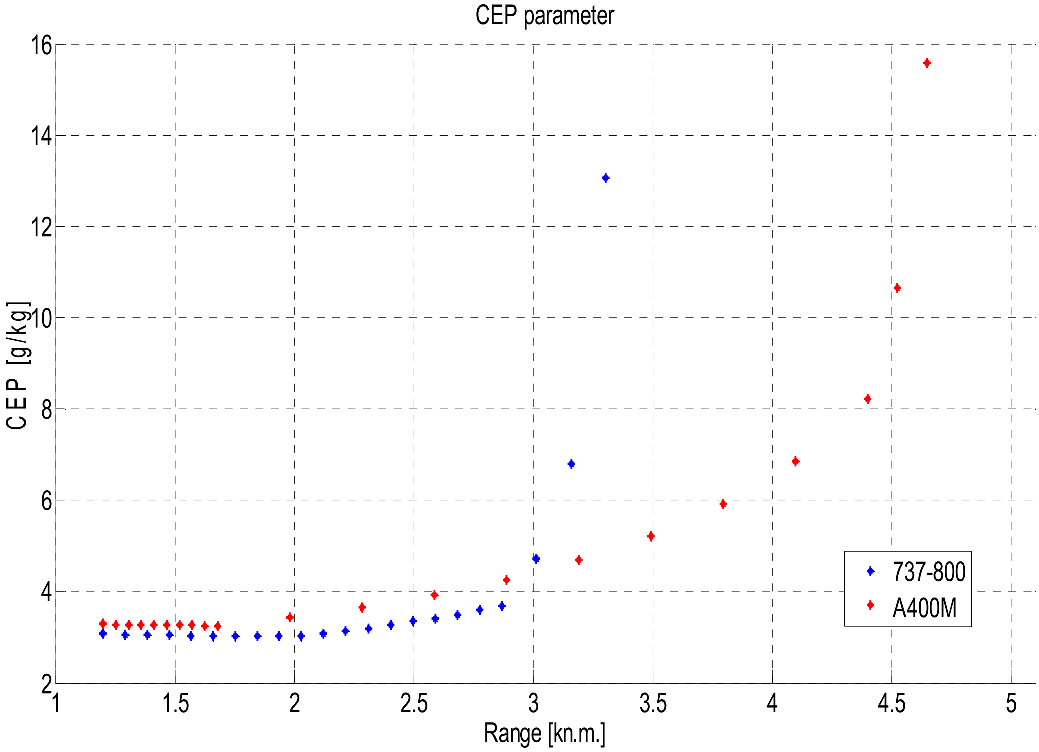

Figure 9-3 CEP parameter comparison

As can be seen from the results, the performance is slightly higher for Boeing 737-800 than for A400M. The difference is dues to the different design targets of the two aircraft: the first has been designed for civilian purpose and it is supposed to take-off and land in civilian airports, where nowadays emissions regulations are applied. The A400M is a military airplane; therefore the designers have most likely not focused on low fuel consumption and emissions but, in all probability, on quick take-off and landing capabilities and on survivability and

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[11] The constants a, b, c, d, etc of equation (3-2) are unity for kerosene, as discussed in [6]

manoeuvrability. This consideration leads to the idea that a turboprop engine powered airplane, specifically designed for low emissions, might have a lower CEP than the baseline.

Over and beyond the considerations above, it is important to take into account that the calculation of the CEP is not complete, because the assessment of NOx emissions has not been feasible. CO2 and H2O emissions depend directly on the fuel burnt, so the behaviour of the simplified CEP is strongly related to the ETRW evolution during the mission. The addition of NOx emissions will change this behaviour and also the way of evaluating the results. Nitrogen oxide formation depends on the engine power setting: thus, the emission index will be different for all phases of flight. As the NO_x is mainly produced at high power setting and is a function of combustor design, it is likely to have the higher EI at take-off and top of climb. For this reason, the CEP will change during the mission.

This consideration is very important because nowadays aircraft regulations are applied only in the airports. However, in the next years some policies are likely to be introduced also at cruise level. Therefore, the assessment of the change in CEP for different phases becomes critical, in order to evaluate the different performance at ground-level and altitude. For this reason, the development of a NO_x model would be part of some further work.

Chapter 10 - CONCLUSIONS

The assessment of aviation environmental impact and reduction of carbon dioxide and NO_x emissions are important goals for future aircraft design. In particular, after the recent economic crisis, the increase in fuel prices pushes aviation companies towards more fuel efficient aircraft. The turboprop configuration is an interesting concept for low fuel consumption: in this context, a main objective of this thesis has been the assessment of the performance of Airbus A400M. In addition, the possible use of the ETRW parameter for aircraft efficiency assessment has been investigated.

In the first part of the dissertation, the Energy Liberated to Revenue Work Ratio has been chosen to quantify aircraft performance and has been presented through a discussed literature review. Additionally, a preliminary study was undertaken on the payload-range capabilities and overall dimensions of the A400M and some medium-to-long range airplanes, in order to choose the baseline (i.e. Boeing 737-800) and to compare the results.

In the second part, the engine and aircraft models were produced and validated using public domain data. The engine was rated in order to allow the model to interrelate with the aircraft one, i.e. the thrust levels for each flight phase were found. Suitable fuel planning and mission profile were defined, while the aircraft models for both airplanes were validated by comparing the simulation results with the payload-range diagrams available in public domain. Finally, the performance of the aircraft in terms of ETRW has been assessed. The results show that A400M is less efficient than common medium range civilian aircraft. However, this lack in efficiency is largely due to the applications and payload requirements of the aircraft and the potential of the turboprops for low emissions lead to the idea of installing the engines on a civilian aircraft body. Despite the possibilities of passengers' negative perception related to the danger of visible blades and to noise production, the significant decrease in fuel consumption might overcome all these disadvantages, by providing a very low ticket price.

The following step involved determining the optimum altitude-speed combination which gives the minimum ETRW and maximum Specific Air Range. The main idea was to assess the effectiveness of the ETRW parameter for energy efficiency measurement. The optimisation process found one optimum solution for the two objectives: therefore, the effectiveness of the ETRW has been confirmed.

Further work included assessing the potential of ETRW in relation to aircraft performance measurement.

First of all, the sensitivity of the load factor on the parameter has been calculated. To fly at part load largely decreases the energy efficiency, because the airplane doesn't make the most of its payload capability. As a result, the current aircraft operations are significantly less efficient than the designed aircraft capabilities.

Another sensitivity analysis has been undertaken in order to evaluate the change in ETRW during aircraft lifespan. The engine degradation affects the fuel consumption by increasing the fuel needed for a given mission. As an outcome of this analysis, it is possible to see how low degradation factors are still acceptable for normal aircraft requirements, while highest values of degradation give an excessive increase of the ETRW. Consequently, it can be interesting to develop a tool which assesses the overall engine degradation by looking to the change of the ETRW parameter. In this way, the operators can save time and money by avoiding regular diagnostics on the engine.

In the last part of the thesis, the objective has been to assess aircraft emissions in terms of Coefficient of Environmental Performance. This parameter employs the ETRW to quantify the amount of fuel burnt during a given mission while taking also into account aircraft operations (payload-range mission parameters). As a case study, carbon dioxide and water vapour emissions have been evaluated using the Fuel Composition Method. The CEP has been calculated both for A400M and baseline. As a result, it is possible to see how this parameter assesses the environmental performance by balancing gross emissions, aircraft operations and design capabilities: therefore, it is a good estimation of aviation environmental impact. On the other hand, NO_x emissions calculation was not feasible through lack of data for model validation. Therefore, the evaluation of the CEP parameter is not complete and further work could be undertaken in this context.

Nowadays, commercial passenger airplanes have still better performance than turboprop powered aircraft. This outcome is due to the fact that commercial turboprops are employed and designed mainly for regional aircraft or military cargo operations. Hence, the design aims of these configurations are totally different: the energy efficiency is not competitive in the medium-to-long range civilian market.

It is nevertheless relevant to infer that the ETRW parameter is a good estimator of aircraft performance. It can be successfully employed for environmental impact assessment and energy efficiency optimisation. In addition, it is important to take into account its behaviour during the aircraft life as a key indicator of engine degradation.

10.1 Further works

As mentioned above, some improvements to this thesis can be undertaken.

First, the NOx emissions model has not been developed, because it was not possible to readily use the available Cranfield emissions software. The first step would have been the validation of the combustion chamber parameters for the TPCU model, however, no data were found in the public domain. Nevertheless, future data availability may solve this barrier and the CEP parameter estimation could be completed.

In the context of engine degradation assessment, the behaviour of the ETRW is mainly related to the increase in fuel consumption. Interesting further work could therefore include developing a model or a tool assessing the correct relationship between the increase in ETRW and the components degradation. The main advantage of this approach is the possibility to quantify the level of degradation by simply looking at the amount of fuel burnt for a given mission profile.

Moreover, one of the main goals of this thesis has been the evaluation of current turboprop powered aircraft performance. The main outcome has been to understand the current design limitations, when compared to turbofan aircraft. A further work can be undertaken on the assessment of the performance of a new design based on the installation of the engines on a civilian aircraft body. This solution can be particularly interesting in the BRIC area, in a context of low ticket prices. Additionally, the reasons for having discarded the propfans in the early 90s have been discussed in the introduction of this thesis. Nowadays, the economic situation has changed and this design can benefit from the current fuel prices. Thus, more possible work can be the evaluation of the propfan configuration performance.

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APPENDICES

Appendix A - ENGINE AND AIRCRAFT SOFTWARE

In this appendix, the engine and aircraft performance models functioning has been described.

A.1 TURBOMATCH software

TURBOMATCH is the Cranfield University gas turbine performance and diagnostics software. It is structured in "bricks" [24], pre-programmed models of gas turbine components (compressor, turbine, combustor, nozzle, etc) and performance simulation calculations (arithmetic operations, performance assessment, results' plots, etc). The user defines the structure and the input parameters of the engine, in order to obtain all the performance outputs required.

TURBOMATCH potential cover a wide range of basic and advanced capabilities; thus, it is useful to simulate design and off-design points of a vast series of aero and industrial engines, comprising novel cycles and more complex gas turbines (multi-spoon, mixed exhaust, combined cycles, etc).

A.2 HERMES software

HERMES is a Cranfield University simulation code for integrated aircraft-engine performance. The aircraft aerodynamics and performance model includes aircraft specifications and mission definition. It cooperates with the engine TURBOMATCH code, in order to simulate overall airframe performance.

The main structure of the code is shown in the table below.

The model is based on six modules:

- *INPUT DATA MODULE*, to define the shape, the geometry, the required performance of the aircraft (including MTOW, payload, fuel load) and the mission profile and range
- *MISSION PROFILE MODULE*, to find the operating conditions of the engines, which are inputs of TURBOMATCH
- *ATMOSPHERIC MODULE*, to define the ISA conditions at given altitude and Mach number
- *ENGINE DATA MODULE*, performed in TURBOMATCH to define the engine performance
- *AERODYNAMIC MODULE*, to define the drag characteristics of the aircraft
- *AIRCRAFT PERFORMANCE MODULE*, to calculate the segments and overall performance in terms of fuel burn, time and range

Table_Apx A-1 HERMES files

Type	File name	Description
Input files	GeomMissionEngineSpec.txt	Aircraft specifications and mission definition
	Engine.dat	Engine DP data
Output files	AircraftFlightPathPerf.txt	Aircraft performance data for the whole mission and for each segment of the flight path
	EngineFlightPathPerf.txt	Engine performance data for the whole mission and for each segment of the flight path
Executables	TmatchCallsV3.exe	The first executable file, it loads engine DP and mission data and generates engine off-design performance data
	HermesV5.exe	The second executable file, it loads aircraft, engine off-design and mission data to generate the output overall performance data

Other input/output files are automatically generated by TmatchCalls and HERMES in order to calculate aircraft and engine performance.

For more information, check the manual [23].

Appendix B - AIRCRAFT PERFORMANCE THEORY

The estimation of the overall performance of an aircraft is part of the initial design phase and involves:

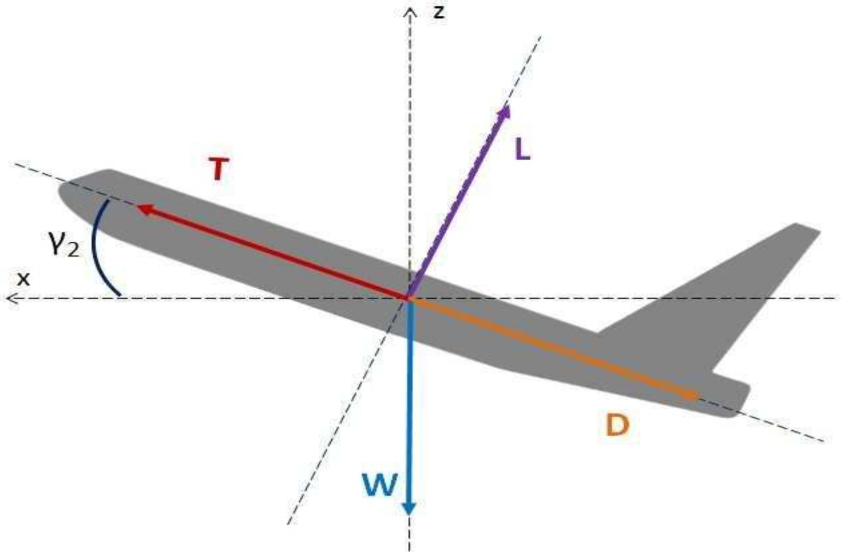
- Proposal of performance targets to be met, along with airworthiness requirements
- Assumptions of the environmental conditions (i.e. ISA)
- Mission and payload definition
- Estimation of airframe aerodynamics characteristics
- Estimation of power plant outputs

In this section, the definition and estimation of the aerodynamics forces and the overall mission aircraft performance has been highlighted.

B.1 The aerodynamics and propulsive forces

The equations of motion of an aircraft are derived from the Newton's law on each of the three axes. Four different forces act on the aircraft: inertial forces, gravitational forces, aerodynamics forces and propulsive forces, the former being the sum of the others. Simplifying assumptions can be made in order to find a reduced version of these equations [42].

The forces system of an aircraft can be simplify as shown in the Figure_Apx B-1.



Figure_Apx B-1 Aircraft aerodynamics forces

The simplified equations of motion on the plan X-Z are:

$$\begin{cases} F_N - D = W sin\gamma_2 + T \\ L = W cos\gamma_2 \end{cases} \tag{B-1}$$

Where L is the lift, D the drag, F_N the standard net thrust, T the aircraft thrust (product of mass and acceleration) and γ_2 the climb gradient of the aircraft (assumed constant).

The **lift force** is produced mainly by the wings and its general expression is:

$$L = \frac{1}{2}\rho\, V^2 S\, C_L = \frac{1}{2}\gamma\, p\, M^2 S\, C_L = q\, S\, C_L \tag{B-2}$$

Where q is the dynamic pressure (which can be defined in function of density ρ and velocity V or pressure p and Mach M), S the wing area and C_L is the lift coefficient, which depends upon the angle of attack α of the wings. The value of α is comprised between the minimum zero-lift and the maximum stall angles of attack. The presence of flaps and slats modifies the value of these angles and allows the wings to suit better to the different regimes.

The **drag** force has three components:

$$D = D_Z + D_i + D_{wv} = q\, S\, C_D \tag{B-3}$$

Where D_Z is the lift independent drag, D_i is the lift dependent drag and D_{WV} is the volume dependent wave drag.

The latter relates to high subsonic and supersonic Mach numbers and is usually neglected for subsonic performance analysis. Hence, the drag polar of the aircraft is parabolic and the drag coefficient is given by:

$$C_D = C_{D_Z} + K\, C_L^2 \tag{B-4}$$

The first term is the *lift independent drag* and depends upon two terms: the surface friction coefficient (depending on Reynolds number and surface dimensions) and the profile drag coefficient (affected by the Prandtl-Glauert factor K).

The former tend to decrease slightly as Mach number increases, while the latter shows the opposite behaviour, in particularly approaching the transonic region. However, the overall behaviour shows an increase if the speed augments.

Estimating methods for the C_{Dz} assess the different aircraft components separately and evaluate for each component the flat-plat skin coefficient Cf, the form factor φ (accounting for the viscous effects) and the component interference factor Q:

$$C_{D_Z} = \frac{\sum\left(C_f\ \varphi\ Q\ S_{wet}\right)_{component}}{S_{ref}} \tag{B-5}$$

The second term of equation (B-4) is the *lift dependent drag* and is a function of the angle of attack of the wings, depending on the lift coefficient C_L. The factor K for incompressible flow is generally *1/(π AR e)*, where *AR* is the wing aspect ratio and *e* is the span efficiency factor. Empirical methods have been assessed in order to evaluate the C_{Di} and most of them calculate K as a function of wing planform geometry, non-optimum wing twist and viscous effects [33]. Since the lift dependant coefficient is inversely proportional to the dynamic pressure, it decreases when Mach number increases.

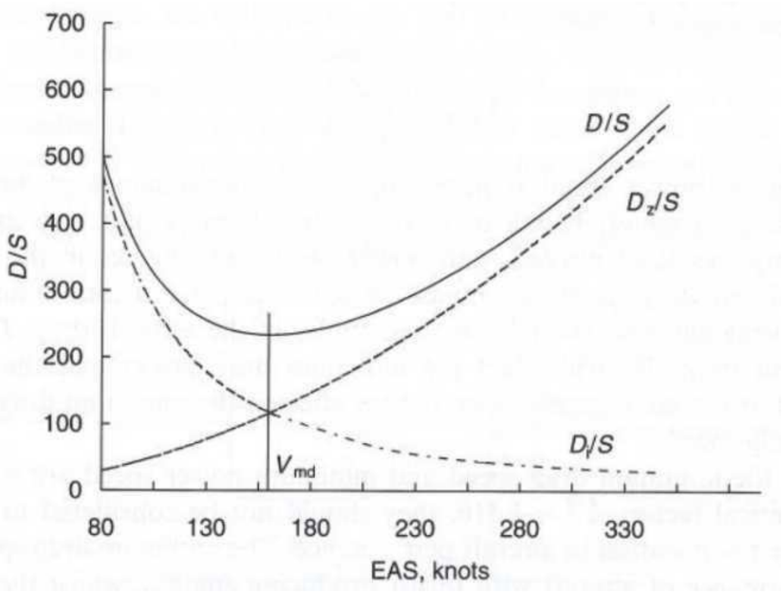
Converting the drag characteristics into force units and using the Equivalent Air Speed V_e, the drag becomes:

$$D = \frac{1}{2}\ \rho\ S\ C_{D_Z} V_e^2 + \frac{K\ W^2}{\frac{1}{2}\ \rho\ S\ V_e^2} = Y\ V_e^2 + \frac{Z\ W^2}{V_e^2} \tag{B-6}$$

Where Y is the lift independent drag factor and Z is lift dependent drag factor.

Hence, a value of minimum drag can be found differentiating the equation, in order to calculate the *Minimum Drag Speed*, which occurs when the two drag components are equal (Figure_Apx B-2):

$$V_{emd} = \sqrt[4]{\frac{Z\ W^2}{Y}} \tag{B-7}$$



Figure_Apx B-2 Minimum Drag Speed, for given weight and altitude [42]

The ratio between the airspeed V and the minimum drag speed V_{emd} gives the Relative Airspeed u:

$$u = \frac{V}{V_{emd}} \qquad \textbf{(B-8)}$$

The aircraft Aerodynamic Efficiency is defined as the maximum lift-drag ratio:

$$E_{max} = \frac{L}{D_{min}} = \frac{1}{2\sqrt{K\, C_{D_Z}}} \qquad \textbf{(B-9)}$$

The Standard Net Thrust of a thrust-producing power plant is given by the difference between the gross thrust and the momentum drag[12]:

$$F_N = F_G - D_m = \dot{m}\, V_j - \dot{m}\, V \qquad \textbf{(B-10)}$$

The mass flow changes with altitude, inlet Mach number and engine rotational speed; the inlet velocity V depends upon the inlet Mach number; the exhaust gas velocity V_j is a function of throttle setting and gas temperature.

---

[12] The main assumptions are that the mass flow in and out of the engine are equal (i.e. fuel flow compensated by bleed extraction) and that the velocity distributions at inlet and nozzle are constant

Power-producing power plant

When shaft-power engines are considered, the power plant produces power instead of thrust, which is the product of a force and a velocity. The shaft-power P is converted in thrust T by the propeller, which has a given conversion efficiency η. Hence, it is possible to define the drag-power as the drag by the true airspeed V and, in terms of EAS and relative density σ:

$$P = \frac{TV}{\eta} = D\frac{V_e}{\sqrt{\sigma}} \tag{B-11}$$

The Minimum Power Speed can be defined as:

$$V_{emP} = \sqrt[4]{\frac{Z\,W^2}{3\,Y}} \tag{B-12}$$

The latter is an important parameter because the equivalent thrust power $\eta P\sqrt{\sigma}$ decreases with altitude and the aircraft will reach a ceiling, related to the minimum power speed, at which the excess thrust power is zero.

B.2 Cruising performance

The cruising performance is fundamental for the overall mission performance estimation, because the majority of the flight time is spent at cruise. They influence the economics of civilian aircraft operations and the endurance and radius of action of military operations.

At cruise condition, the flight is assumed steady, level, straight and symmetric. Also, acceleration change and manoeuvres are neglected. The equations of motion (B-1) become:

$$\begin{cases} F_N = \mathrm{D} \\ L = W \end{cases} \tag{B-13}$$

Cruise performance can be measured in terms of Specific Air Range (i.e. the horizontal distance flown par unit of fuel used) or Specific Endurance (i.e. the time of flight par unit of fuel used):

$$SAR = -\frac{dx}{dm} = \frac{V}{Q_f} \tag{B-14}$$

$$SE = -\frac{dt}{dm} = \frac{1}{Q_f} \tag{B-15}$$

Where Q_f is the fuel flow rate. Generally, in order to provide simple and reasonable performance estimation methods, Q_f is assumed proportional to F_N; thus, it is also possible to define the Specific Fuel Consumption as a constant function:

$$\mathrm{SFC} = \frac{\mathrm{Q_f}}{F_N} \tag{B-16}$$

The fuel ratio ω can be defined as the initial upon the final aircraft weight:

$$\omega = \frac{\mathrm{W_i}}{\mathrm{W_f}} \tag{B-17}$$

$$W_i - W_f = W_i \,(1 - \frac{1}{\omega}) \tag{B-18}$$

The weight of the aircraft can be considered from the definition of lift:

$$W = \frac{1}{2}\gamma\, p\, M^2 S\, C_L \tag{B-19}$$

It can be seen how the second term has to decrease, accordingly to the weight reduction during the flight, in order to balance the equation. The variable can be the air pressure (i.e. cruise altitude), the flight Mach number or the lift coefficient (i.e. angle of attack), keeping the other two constant. Three cruising methods are based on that simple consideration.

Method 1: constant angle of attack and Mach number

With this method, the altitude will increase to allow the air pressure to decrease and balance the weight reduction during the time:

$$\frac{W}{p} = \frac{1}{2}\gamma\, M^2 S\, C_L \tag{B-20}$$

This implies that the term W/p has to be kept constant and a climb-cruise technique will be performed.

The range flown R for a given mass of fuel is:

$$R_1 = \frac{1}{g}\left[\frac{V_{emd}}{SFC} E_{max}\right]\left\{\frac{2u^3}{u^4 + 1}\right\} ln\omega \tag{B-21}$$

The endurance E is:

$$E_1 = \frac{1}{g}\left[\frac{E_{max}}{SFC}\right]\left\{\frac{2u^4}{u^4+1}\right\} ln\omega \tag{B-22}$$

When the aircraft flies at minimum drag speed, the endurance is maximized.

On a theoretical basis, this method gives the longest achievable range. However, it is difficult to change altitude freely, due to technical and airworthiness restrictions. Thus, aircraft usually perform a stepped climb-cruise, in order to obtain acceptable values of W/p, constant in average during the cruise.

Further considerations have to be made about the change in temperature in the troposphere, influencing the assumptions above. While the altitude increases, the temperature decreases so the engine cycle improves (i.e. thrust augments). Thus, it is essential to reduce the engine rotational speed, in order to maintain a constant Mach number.

Method 2: constant angle of attack and altitude

This time, the Mach number will decrease in order to balance the weight reduction during the time:

$$\frac{W}{M^2} = \frac{1}{2}\gamma\, p\, S\, C_L \tag{B-23}$$

The decrease in TAS, to keep the Mach number constant, augments the overall time of flight, with consequently cost penalties which are likely to overweight any fuel cost saving. On the other hand, the constant altitude is beneficial for military operations (as surveillance).

The endurance is the same that the first method, while the range flown for a given mass of fuel is:

$$R_2 = \frac{1}{g}\left[\frac{V_{emd}}{SFC}E_{max}\right]\left\{\frac{2u^3}{u^4+1}\right\}2(1-\frac{1}{\sqrt{\omega}}) \tag{B-24}$$

Method 3: constant Mach number and altitude

For this method, the C_L and C_D reduce so engine thrust reduces as fuel is burnt and lift and drag of the aircraft will change:

$$\frac{W}{C_L} = \frac{1}{2}\gamma\, p\, M^2 S \tag{B-25}$$

The range flown for a given mass of fuel is:

$$R_3 = \frac{1}{g}\left[\frac{V_{emd}}{SFC}E_{max}\right]\left\{\mathrm{atan}\frac{1}{u^2} - \mathrm{atan}\,\frac{1}{\omega u^2}\right\}2u \tag{B-26}$$

The endurance is:

$$E_3 = \frac{1}{g}\left[\frac{E_{max}}{SFC}\right]2\left\{\mathrm{atan}\frac{1}{u^2} - \mathrm{atan}\,\frac{1}{\omega u^2}\right\} \tag{B-27}$$

Narrow conditions are required in order to perform this method, because of the change in the aircraft aerodynamics forces. The airspeed has to be higher than the minimum drag airspeed, to avoid steep drag increase. Nevertheless, the maximum endurance occurs when the former condition is opposite, so this method is likely to be speed unstable.

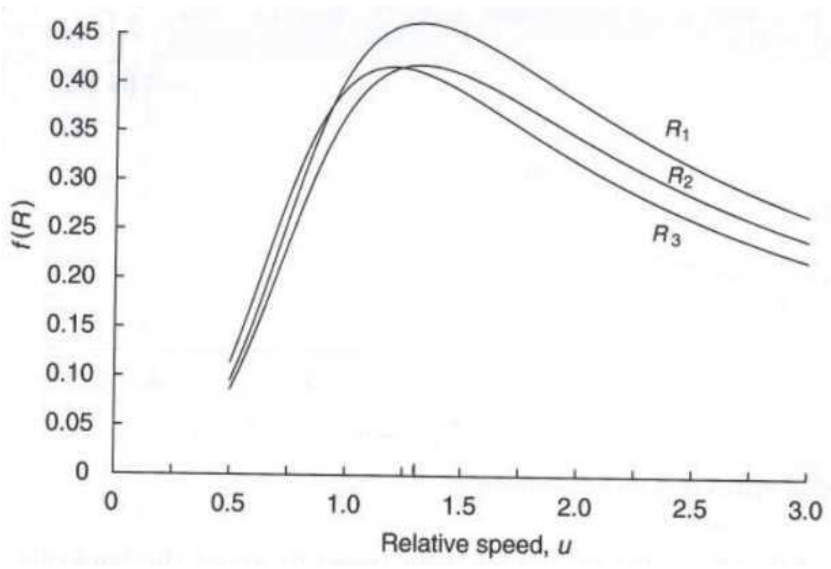
Comparison and considerations

For all the equations above, the terms in brackets are called “Range/Endurance Factor”, depending on drag characteristics and SFC (i.e. aircraft design). The terms in brace are relative speed dependant functions and the last terms are fuel ratio dependant functions: they influence aircraft operation and allow quantifying the fuel needed for a given mission.

Range and endurance of the three methods can be compared for an aircraft of given initial weight.

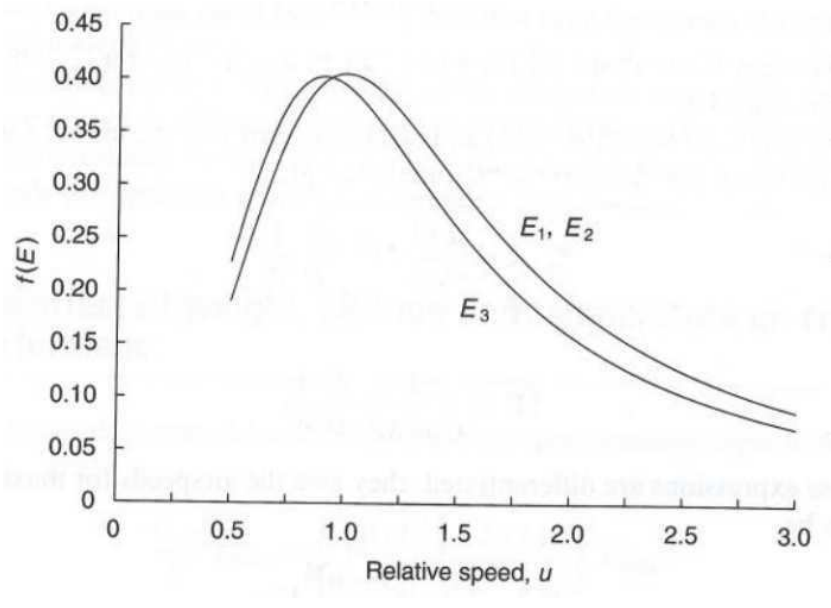
The Figure_Apx B-3 shows how the first method has a 10% higher *range* than the others, being the optimum method for cruise. As highlighted in the section above, it is also impractical because of the unfeasibility to change altitude freely. On the other hand, the second method is not economically viable, though the third has a very short maximum range compared to the others. Finally, the first method is the most used for civilian long range mission performance estimation, replaced from time to time by the third but only for short range mission.

The “range factor” is a function of initial aircraft weight, ambient temperature and pressure, i.e. altitude. Assuming a constant SFC, an accurate analysis shows that the range decreases if the initial weight increases, while it increases with increasing altitude and ambient temperature. Further considerations show how an optimum altitude can be calculated, combination of optimum TAS for minimum drag and critical Mach: this altitude refers to the minimum SFC and flight time.



Figure_Apx B-3 Range, methods comparison [42]

Regarding the *endurance*, the first two methods have the same theoretical value, which is slightly higher than the one for the third method (see Figure_Apx B-4). Also, the latter is speed instable for maximum endurance, so it is infeasible. Being the endurance a preeminent parameter for military operations, able to overweight time and range losses, the second method is likely to be the most performed in this case.



Figure_Apx B-4 Endurance, methods comparison [42]

Mixed Thrust and Power-producing power plant

In the case of shaft-power engines, the SFC is defined in terms of power instead of thrust, so that also SAR and SE are function of engine power and conversion efficiency. When the engine has both thrust and power-producing characteristics, as in the case of a turboprop, range and endurance are a combination of these different effects. For example, for the first cruising method:

$$R_{1_{TP}} = \frac{E_{max}}{g}\left[\Pi \frac{\eta}{SFC_P} + (1-\Pi)\frac{u\,V_{emd}}{SFC_T}\right]\left\{\frac{2u^2}{u^4+1}\right\} ln\omega \tag{B-28}$$

$$E_{1_{TP}} = \frac{E_{max}}{g}\left[\Pi \frac{\eta}{SFC_P\ V_{emd}} + (1-\Pi)\frac{u^3}{SFC_T}\right]\left\{\frac{2u}{u^4+1}\right\} ln\omega \tag{B-29}$$

Where Π is the proportion of the shaft thrust over the total thrust and the two SFC terms are the specific fuel consumption based on power-producing (index P) and thrust-producing power plant (index T).

B.3 Climbing and descent performance

In order to increase or decrease the altitude during the mission, the difference between engine thrust and airframe drag is used to change the aircraft potential and kinetic energies. When the thrust is higher than the drag, the aircraft climbs to a higher altitude; otherwise, it descends toward a lower altitude. Economics and safety considerations affect the aircraft performance, in particular during the climb phase, when the engine works at maximum power.

In practice, climb (or descend) is performed in three phases: first the aircraft climbs at a given altitude at constant EAS, then it increases its speed at constant altitude and finally it climbs at its final altitude at an higher, constant EAS.

For subsonic aircraft *climbing performance* estimation, some considerations are generally made:

- The thrust-to-weight ratio is low at take-off
- The climb rate is low, so that the acceleration term can be neglected
- The flight is quasi-steady state

The climb gradient γ_2 can be written in function of the rate of climb dH/dt:

$$\gamma_2 = \text{asin}\left(\frac{\frac{dH}{dt}}{V}\right) \tag{B-30}$$

Where H is the geopotential height. From equation (B-1) it is possible to calculate the rate of climb as:

$$\frac{dH}{dt} = (F_N - D)\frac{V}{W} \tag{B-31}$$

The best climb gradient occurs when the aircraft flies at minimum drag speed. However, operational and safety issues, such as presence of obstacles, have to be considered and the aircraft has to be capable to climb with a gradient of at least 2%.

The best rate of climb occurs when the aircraft thrust-to-drag power ratio is maximised. In this condition, the aircraft is able to reach its operating altitude in the minimum time. On the other hand, the climb fuel consumption is defined as:

$$SFC = \frac{\frac{dH}{dt}}{Q_f} \tag{B-32}$$

Economic issues push toward the need of minimum fuel consumption, so the operational rate of climb is a trade-off between minimum time and minimum fuel.

Considering *descent performance* estimation, the optimisation is not as forthright as for the climb: the engine works at lower power than its maximum, so that the fuel consumption is not any more a critical parameter. However, this phase is critical because of safety issues: the gradient of descent has to be controlled continuously to ensure flight path stability and acceptable levels of cabin re-pressurisation. A common value of the descent gradient is around 5% for large transport aircraft. In addition, the engine has to ensure an acceptable amount of power for aircraft auxiliary systems operation.

Further considerations can be made in regards to wind effects or supersonic climb performance, but they are not relevant for the purpose of this thesis.

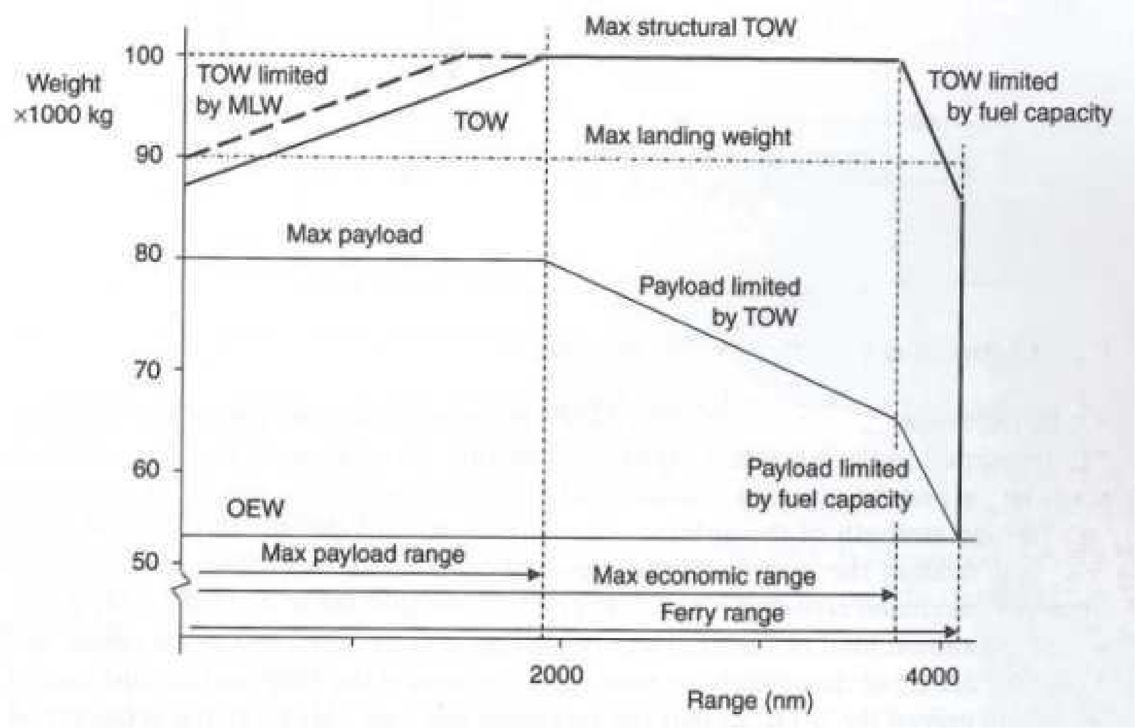
B.4 Payload-Range diagram

The payload-range diagram defines the viability of an aircraft to carry out a specific mission (i.e. the potential range for operations).

From the aircraft weight breakdown, it is possible to define:

- OEW, the ready-to-fly aircraft weight, without fuel and payload, but including crew, luggage, unusable fuel and special equipment
- MTOW, the maximum total weight of the aircraft at take-off
- MLW, the maximum total weight of the aircraft at landing
- MDL, the maximum load possible for the aircraft, divided in:
  - MSP, the maximum structural payload than the aircraft can carry
  - MFL, the maximum fuel load, that has to be less than the MFC of the tanks and is limited by the payload carried
  - MZFW, the maximum zero fuel weight (given by the OEW plus the MSP)

In the Figure_Apx B-5, it is possible to see how the payload-range diagram is built and which limitations are involved.



Figure_Apx B-5 Payload - Range diagram definition [42]

The first part of the chart refers to the maximum payload range. The payload is fixed at its maximum value and the fuel required increases with the range, until the aircraft reaches the MTOW.

The second part refers to the economic range. It is necessary to reduce the payload in order to allow the increase of the fuel required to improve the range. This can be done until the fuel carried reaches the MFC limit, i.e. the maximum economic range of the aircraft.

The third part refers to the ferry range. The fuel carried is kept constant at its maximum value, while the payload continues to decrease, until it becomes zero. This is the maximum operational range achievable by the aircraft.

It is important to highlight how, for short ranges, the MTOW is limited by the MLW. In addition, the chart enables to quantify the payload to be sacrificed to achieve a defined range.

Appendix C - AIRCRAFT DESCRIPTION

In this appendix, it is possible to find the description and the overall specifications of the baseline Boeing 737-800 and of Airbus A400M.

C.1 Boeing 737-800

The Boeing 737 is a narrow-body aircraft, performing medium ranges. The 737 series is the best-selling airline in the history of aviation, manufactured from 1967 and with thousands of orders and deliveries. The 737-800 variant was launched in 1994 to replace the 737-400 and the MD-80 and MD-90 after the incorporation of McDonnell Douglas. It first entered in service in 1998.

The aircraft has a passenger's capability of 162 seats for the two-class layout and 189 seats in one class. Continue improvements are made both to the airframe and the engine: advanced-technology wings design and fuel saving engine configurations have been developed in the last years. Also, the new versions are equipped of blended winglets, allowing better fuel and take-off performance and longest ranges, as long as reduced maintenance costs and noise. The last available enhancement is the Boeing Sky Interior, increasing passengers' comfort.

Engine: CFM 56-7B27 [43]

The CFM56 engines are a series of high BPR turbofans, developed by CFMI, a joint venture between GE and Snecma. Developed in the 70s, this family is now one of the most sold engine's series in the world. The 7B27 was developed in order to provide improved fuel efficiency and thrust to the 737 Next-Generation family.

Figure_Apx C-1 CFM 56-7B27

The core has two shafts, 3 stages LPC and 9 stages HPC, coupled to a single-stage HPT and 4 stages LPT. The compressor is annular; the OPR is 32.8 and the maximum achievable thrust is 86.7 kN.

C.1.1 Specifications

In the tables below it is possible to find the data of Boeing 737-800 from public domain [7], regarding overall dimensions, weight and performance.

Table_Apx C-1 737-800 overall specifications

Parameter	**Value**	**Units**
DIMENSIONS		
Fuselage length	38.08	m
Fuselage height/diameter	4.01	m
WEIGHTS		
OEW	41413	kg
MTOW	79016	kg
MLW	65361	kg
MFC	20894	kg
MSP	21319	kg
Engine weight (CFM56 x2) [43]	3654	kg
PERFORMANCE		
Cruise altitude	10668 (35000)	m (ft)
Cruise speed (Mach)	0.78	-
RANGE (5% reserve, 200 n.m. diversion and 30 min hold at 457 m)		
Max PL range	3797 (2.05)	km (kn.m.)
Max economic range	5371 (2.90)	km (kn.m.)
Max ferry range	6390 (3.45)	km (kn.m.)

Table_Apx C-2 737-800 geometrical features

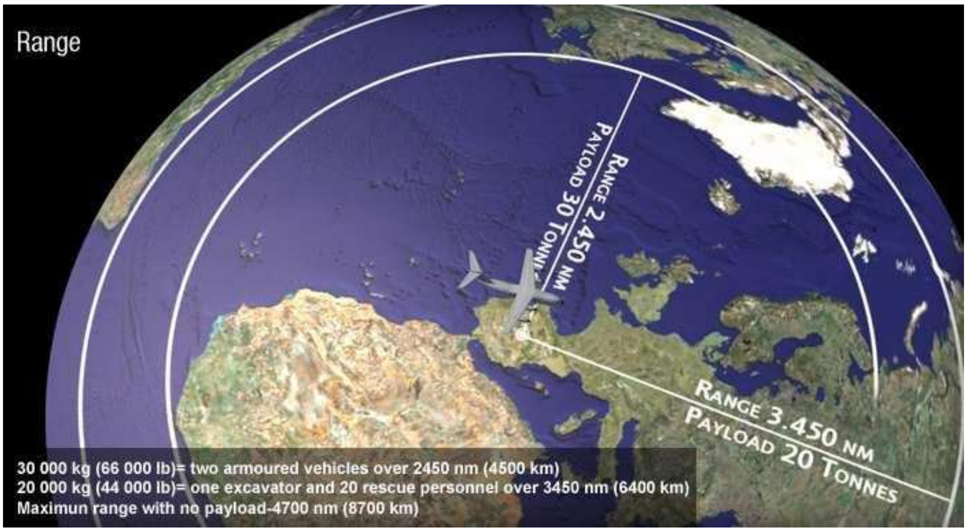
Geometrical Parameters	Wings	Tail plane	Fin	Units
Area	124.58	32.78	26.44	m^2
Aspect Ratio	9.45	5.00	-	-
Span	-	-	7.16	m
Thickness/Chord	0.11	0.11	0.12	-
Sweep angle (at 25% chord)	25	30	35	degrees
Taper Ratio	0.16	0.20	0.28	-
Root T/C	0.15	0.12	0.15	-
Outer T/C	0.10	0.10	0.15	-

C.2 Airbus A400M

The A400M is the most versatile airlifter currently commercially available. It can perform tactical, strategic, logistic and air-to-air refuelling missions and it has a wide speed and altitude flight envelope. For ease of access, detailed information is included in the sub-chapter below but is taken directly from Airbus Military website [13].

C.2.1 Characteristics and operations

Capabilities: the A400M can carry several outsize cargos, including vehicles and helicopters, and can also carry 116 personnel or fully equipped paratroops. It can fly distances up to 8700km at high altitude and Mach speed, with similar performance of modern turbofan powered airlifters. It can fly above adverse medium level weather conditions and be integrated into the commercial aircraft airspace.



Range

30 000 kg (66 000 lb)= two armoured vehicles over 2450 nm (4500 km)
20 000 kg (44 000 lb)= one excavator and 20 rescue personnel over 3450 nm (6400 km)
Maximun range with no payload-4700 nm (8700 km)

Figure_Apx C-2 A400M typical ranges [13]

The four TP400-D6 are less sensitive to ingestions than jet engines and the twelve-wheel main landing gear has an highly efficient absorption of shock-loads into the airframe structure for operations on several strips (short, soft or rough unprepared field) and is designed to minimize risk of foreign object damage.

The A400M is designed for very rapid and autonomous cargo loading or unloading without any specialized ground support equipment, minimising vulnerable time on the ground, hence increasing its survivability. It takes under two hours to convert the A400M from an airlifter into a two-point tanker aircraft and it can refuel the entire range of military aircraft and helicopters at their preferred speeds and altitudes.

Figure_Apx C-3 A400M landing [13]

<u>Survivability:</u> the A400M has been specifically designed for:

- low detectability and vulnerability and high survivability
- high manoeuvrability
- low level flight capability
- steep descent and climb performance, short landing and take-off performance
- bullet-resistant, excellent self-protection and survivability: the A400M is hard to find, hard to hit and hard to kill

Development programme:

- First fully documented proposal in mid-1998, including the aircraft specification and performance guarantees, the commercial proposal with firm and fixed prices, a full set of contractual terms and conditions and detailed planning of the single-phase programme
- February 1999 delivery of the A400M new programme schedule proposal
- The programme was officially launched on May 2003, by OCCAR (Belgium, France, Germany, Luxemburg, Spain, Turkey and the UK), with Malaysia joining in 2005
- Flight testing from Nov 2009 at EADS-CASA's Seville plant and Airbus' Toulouse facility, six prototypes built, of which five will be refurbished and sold on completion of test duties

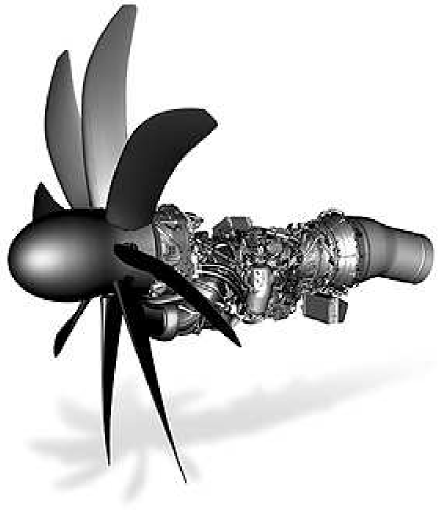
EADS-CASA at Seville will have sole production line, assembling components from the UK (wings), France (cockpit management and flight control systems), Germany (main fuselage), Spain (horizontal stabiliser), Belgium (wing leading edges and flaps), Italy (aft fuselage and other subsystems), Turkey (structural elements) and Portugal (wing/fuselage and undercarriage fairings).

Customers: planned deliveries for France, Turkey, Germany, UK, Australia, Canada, Norway and Sweden; 174 total orders in April 2012

Costs: total development cost expected to be Euro 20 billion. Unit price estimated to be Euro 118.5 million, including 16 per cent VAT. It has a new maintenance concept, largely inspired from commercial civil airliner experience, which will reduce life cycle costs (it requires only 84 days in total on the ground over twelve years of operation).

Design Features: high-wing, T-tailed aircraft with rough-field landing gear and large cabin/hold floor area and cross-section, permitting high payload factors with low-density cargo, vehicles or mixed passenger/cargo loads. Use of propellers is essential for adequate thrust-reverse performance, for taxiing and short landing, for maximising power response and for minimising FOD vulnerability. Minimum service life is 30000 hours.

Structure: Aluminium alloy, with titanium alloy in highly loaded areas (around windscreen, wing/fuselage joint and landing gear anchorage) and glass fibre or carbon fibre for lightly loaded components (landing gear doors and various fairings). Extensive use of composites (30% of the whole structure) in the wings in particular for skins, stringers, spars and moving surfaces; metal for ribs, engine mountings and fuselage pick-ups. Modern design and manufacturing techniques expected to afford major reductions in maintenance man-hour requirements and increases in aircraft availability/survivability.



Engine: TP400D6 [26]

The TP400D6 engine is a twin-spool gas generator, with third coaxial shaft for power turbine. The overall dimensions are 3.5m (length) x 0.92m (diameter). The engine basic weight is 1860kg. The gas generator consists of 5 stages IPC, with fixed stators, and 6 stages HPC, with two rows of variable stators. The HP and IP turbines have both one stage, followed by 3 stages PT. The HP turbine is cooled.

Figure_Apx C-4 TP400D6

The TP400-D6 capabilities allow the aircraft to fly over a wide range of speeds and altitudes and give very efficient fuel consumption.

The counter-rotation of the propellers allows a structural weight reduction and offers improved lift at low speed and reduced level of vibrations and noise.

C.2.2 Specifications

In the tables below it is possible to find the data of the A400M from public domain [13; 35; 36], regarding overall dimensions, weight and performance.

Table_Apx C-3 A400M overall specifications

Parameter	Value	Units
DIMENSIONS		
Fuselage length	24.85	m
Fuselage height/diameter	5.00	m
WEIGHTS		
OEW	78000	kg
MTOW	141000	kg
MLW	123000	kg
MFC	50500	kg
MSP	37000	kg
Engine weight (TP400D6 x4) [26]	1860	kg
PERFORMANCE		
Operating Altitude	9449 (31000)	m (ft)
Max Cruise Speed (TAS)	154 (300)	m/s (knots)
Max cruise speed (Mach)	0.72	-
Cruise speed (Mach)	0.68	-
RANGE (5% reserve, 200 n.m. diversion and 30 min hold at 457 m)		
Max PL range	3300 (1.78)	km (kn.m.)
30 000 kg range	4500 (2.45)	km (kn.m.)
20 000 kg range	6400 (3.45)	km (kn.m.)
Max ferry range	8700 (4.70)	km (kn.m.)

Table_Apx C-4 A400M geometrical features

Geometrical Parameters	**Wings**	**Tail plane**	**Fin**	**Units**
Area	221.50	67.48	46.50	m^2
Aspect Ratio	8.10	5.24	-	-
Span	-	-	6.89	m
Thickness/Chord	0.11	0.11	0.12	-
Sweep angle (at 25% chord)	15	24	34	degrees
Taper Ratio	0.33	0.46	1.00	-
Root T/C	0.15	0.12	0.15	-
Outer T/C	0.10	0.10	0.15	-

Further information:

- 12 wheels configuration landing gear (Messier-Bugatti-Dowty): high flotation and shock absorber capabilities
- flap slots par wing

Appendix D – OPTIMISATION VALIDATION

In this appendix, it is possible to find the validation procedure which has been followed in order to confirm the results of chapter 6.5.2 for the Airbus A400M.

As explained, the trend of the ETRW and the SAR parameters is monotonic and the optimum is close to the maximum achievable Mach number. Hence, it is necessary to verify that the actual maximum of the Specific Air Range coincides with the minimum of the ETRW. In this way, the procedure can be validated, showing that the optimiser works properly.

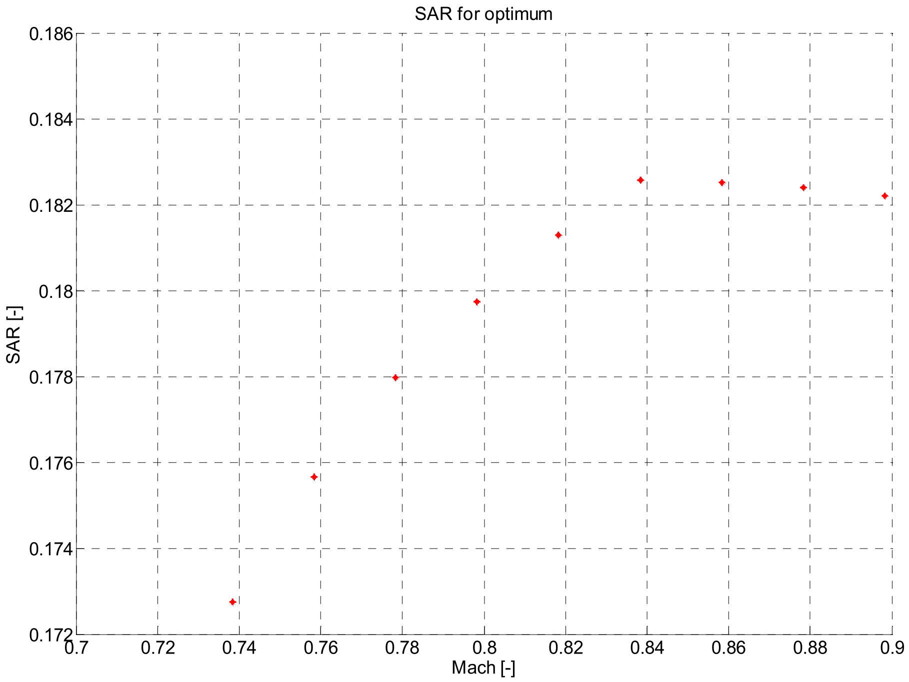
The Mach range has been increase until 0.9, in order to check the increase of the fuel burnt for Mach numbers over the optimum condition.

The optimisation converges around a new optimum at 10338 m of altitude and 0.838 of Mach number.

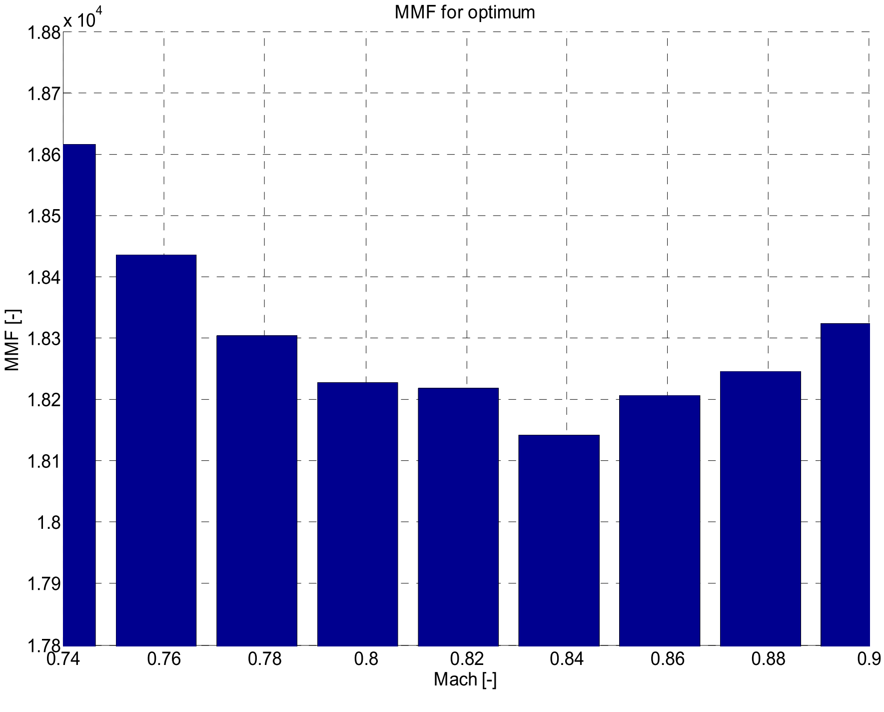
The Specific Air Range and the mass of fuel burnt during the mission have been recalculated for several Mach numbers, at optimum altitude condition.

The results show an increase in the SAR until the optimum value found by the optimiser and then a decrease for higher values of Mach. On the other hand, the fuel burnt decreases until the optimum is reached and then starts again to increase. This trend confirms the accuracy of the optimiser, showing how the minimum fuel gives also the maximum Specific Air Range. Thus, the energy efficiency is maximized at this point.

For the purpose of this dissertation, the speed cannot be higher than the maximum operative cruise Mach number. However, the engine model evaluates properly all possible altitude-Mach combinations, so the user must define the upper limit of the Mach range in the proper way. As a consequence, the trend of the two parameters will be monotonic until this limit and no extrema will be found.



Figure_Apx D-1 SAR over Mach, at optimum altitude



Figure_Apx D-2 MMF over Mach, at optimum altitude