UNIVERSIDADE FEDERAL DE UBERLÂNDIA
FACULDADE DE ENGENHARIA MECÂNICA

MATHEUS ARAUJO CAIXETA

MODELLING A COUPLING ROUTINE BETWEEN TOOLS USED IN AIRCRAFT DESIGN

Uberlândia
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Undergraduate thesis submitted to the Course of Aeronautical Engineering from the Universidade Federal de Uberlândia as part of requirement for obtaining the Bachelor’s degree on Aeronautical Engineering.

Field of study: Aircraft Design. Aeronautical Propulsion.

Tutor: Prof. Dr. Roberto de Souza Martins

Co-Tutor: MSc. Aleksandar Joksimović (ISAE-SUPAERO)

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To all the people I love and who are indispensable in my personal and professional life. A special mention to my incredible parents and to my dear husband.

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ABSTRACT

Recent changes in the aircraft design procedure have made the development of the propulsion system increasingly detailed already in the conceptual phases of the project. Moreover, the use of simulation software in this process has increased considerably in recent years, due to technological advances in processing capacity, optimization algorithms and artificial intelligence. Therefore, a coupling between aircraft design software, PROOSIS and Pacelab APD, was intended to improve the simulations made during these initial phases. Thus, considering the requirements of a commercial transport aircraft, an engine was modelled, dimensioned, and analysed in order to obtain its performance characteristics for different flight phases. The data obtained was then incorporated into the design of the chosen aircraft, using a data import tool. Then, the impacts of this incorporation in the calculation of the aircraft's mission were analysed in order to identify not only the gains achieved, but also the possible failures of the chosen procedure. With the developed manual coupling routine, the designed aircraft had an increase of 7.5% in its range, due to the better representativeness of the data obtained for fuel consumption in cruise condition. In addition, other coupling possibilities, improvements on the coupling achieved and its capacity of generalization were also discussed.

Key words: PROOSIS. Pacelab APD. Aircraft Design. Engine design. Engine performance simulation.

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RESUMO

Mudanças recentes no processo de concepção de uma aeronave tornaram o desenvolvimento do sistema de propulsão cada vez mais detalhado já nas fases conceituais do projeto. Além disso, o uso de software de simulação nesse processo aumentou consideravelmente nos últimos anos, devido aos avanços tecnológicos alcançados em capacidade de processamento, algoritmos de otimização e em inteligência artificial. Portanto, visou-se estabelecer um acoplamento entre dois programas computacionais usado em projetos de aeronaves, PROOSIS e Pacelab APD, tendo como objetivo melhorar as simulações feitas durante essas fases iniciais. Assim, considerando os requerimentos de um avião de transporte comercial, um motor foi modelado, dimensionado e analisado a fim de se obter suas características de desempenho para diversas fases de voo. Os dados obtidos foram então incorporados ao projeto do avião em questão, através de uma ferramenta de importação de dados. Em seguida, os impactos desta incorporação no cálculo da missão da aeronave foram analisados a fim de se identificar não somente os ganhos alcançados, mas também as possíveis falhas do procedimento escolhido. Com a rotina de acoplamento manual desenvolvida, o projeto apresentou um acréscimo de 7,5% no alcance da aeronave analisada, devido a melhor representatividade dos dados obtidos para o consumo de combustível dos motores em regime de cruzeiro. Além disso, outras possibilidades de acoplamento, melhorias no acoplamento alcançado e sua capacidade de generalização também foram discutidas.

Palavras-chave: PROOSIS. Pacelab APD. Projeto de Aeronaves. Dimensionamento de motores. Simulação do desempenho de motores.

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ACRONYMS AND SYMBOLS

ALT	Flight altitude
AOC	Angle-of-climb
AOD	Angle-of-descent
BFL	Balanced field length
BPR	Engine bypass ratio
Cmp	Compressor
EP	Polytropic efficiency
FF	Fuel flow
HP	High pressure
ISA	International Standard Atmosphere
LP	Low pressure
MCL	Maximum climb condition for the engine
MCR	Maximum cruise condition for the engine
MN	Flight Mach number
MTO	Maximum take-off condition for the engine
NH	Rotational speed of the high pressure shaft
NL	Rotational speed of the low pressure shaft
OEI	One engine inoperative
PR	Pressure ratio
RC	Rating thrust
ROC	Rate-of-climb
ROD	Rate-of-descent
SFC	Specific Fuel Consumption
TET	Turbine entry temperature
TLAR	Top Level Aircraft Requirements
TLER	Top Level Engine Requirements
TrbH	High pressure turbine
TrbL	Low pressure turbine

SUMMARY

1 INTRODUCTION

With the advancement of technology, new propulsive architectures have been proposed and used in a new generation of aircraft that arises to meet the new market and society demands in terms of energy efficiency and environmental sustainability. Thus, reduce the consumption of polluting materials and optimize the propulsion systems is a current and urgent need.

Many researches around the world aim to consolidate and enable innovative concepts of aeronautical propulsion architectures that address this new scenario. Distributed propulsion (Figure 1), hybrid propulsion (Figure 2) or even fully electric propulsion are examples of new technologies that have been researched and developed (GUDMUNDSSON, 2014).

Figure 1 – SCEPTOR Distributed Electric Propulsion Aircraft.

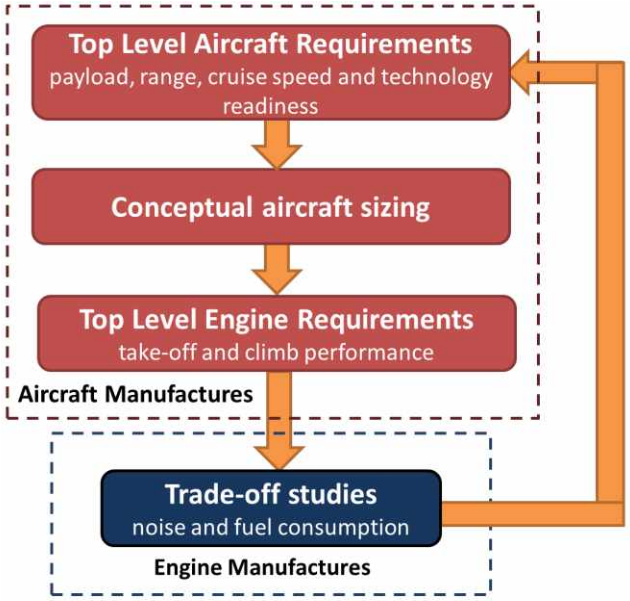
Source: NASA (2020).

Figure 2 – Airbus E-Fan X: a hybrid-electrical aircraft demonstrator.

Source: AIRBUS (2020).

This new industrial context requires that the classical methods of conception of aeronautical systems and products be rethought, since the current systems interdependence prevents an isolated analysis of during their development (SCHNEEGANS, 2012). In effect, the new concepts of propulsion establish a strong coupling between the design of the engine and the aircraft, making indispensable the incorporation of the propulsion system at the beginning of the aircraft design process (SEITZ, 2011), as can be seen in Figure 3. In addition, decisions during design phases strongly impact the development and performance of a new system, making it mandatory to have a technical assessment capability of these concepts already in the initial stages of the project, as described by Seitz (2011).

Figure 3 - Conception process used in modern aircraft.



Source: adapted from Seitz (2011).

To help in the design process, several software is used to simulate the operation of the different systems that make up an aircraft. In fact, with the computational advancement, numerical simulation became increasingly present in industrial processes, being already indispensable in some phases of the project (HOSSEINPOUR; HAJIHOSSEINI, 2009). However, each tool is generally focused on one or some specific systems, and there are few alternatives that can provide plausible means for simulating an architecture composed of several systems of different physical natures. Therefore, a coupling between design processes today also means a coupling between simulation software.

In this context, the idea of coupling two distinct aircraft design software has emerged and was developed in this research project. The tool used was PROOSIS, for the propulsion, and Pacelab APD, for the aircraft. This study goal was to model a coupling routine between the tools mentioned above. It involved the analysis of solutions ranging from manual communication to automated data exchange processes.

The second chapter is dedicated to present the literature on the matter. The problem statement and the modelling of a coupling routine is presented in the third chapter. The fourth chapter summarizes the results and discussions on the developed routine, focusing on the validation of the data obtained and on the possibilities of improving the routine.

2 LITERATURE REVIEW

This chapter is intended to investigate the existing relationship between the propulsion system and the aircraft and its impact during a design project. Thus, it is made up of a first part which discusses the correspondence between the design and the performance of an engine and an aircraft, and a second part which examines the tools of design and simulation of these systems.

2.1 Engine/Aircraft Design and Performance Matching

The propulsion system is one of the most important on an aircraft. Indeed, it is responsible for generating the necessary force used to speed the plane and, consequently, generate lift (GUDMUNDSSON, 2014). In addition, it can also be responsible for the operation of other systems such as electrical, air conditioning, hydraulic, pneumatic, and anti-icing (MOIR; SEABRIDGE, 2008).

So, it is clear and undeniable that the power plant has a major impact on the aircraft design and operation. In fact, engine physical and performance characteristics affect the aircraft sizing, shape, weight, and performance (OATES, 1989). On the other hand, as affirmed by the same author, airframe characteristics and aircraft's mission requirements influence not only the engine sizing but also affect the installed performance of the propulsion system. The Chart 1 summarizes the main influences of the propulsion system in the design of an aircraft and vice-versa.

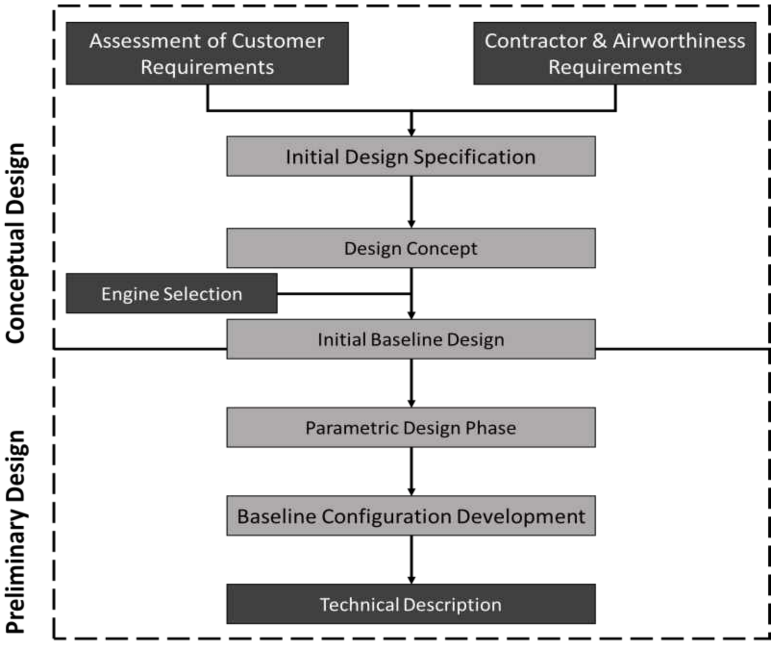
Chart 1 – Propulsion system influence in aircraft design disciplines.

Aircraft Design Discipline	Propulsion System Influence
Geometry	Landing gear height, tail plane configuration and sizing, wing, fuselage and pylon structural geometry.
Structures and weights	Structural loads and weights for main airframe components: wing, fuselage, landing gear, empennage, propulsion mounting structures.
Aerodynamics	evaluation of aircraft high speed aerodynamics and low-speed characteristics.
Performance	simulation of typical point performances, airport operation, maneuver, overall mission performance.
Acoustics	landing and take-off certification noise; in-flight cabin noise.
Life cycle cost	research and development investment, production cost, product ownership cost, maintenance and operation cost and end-of-life aspects.

Source: adapted from Seitz (2011).

Therefore, due this major impact, it is natural that the choice or development of a power plant is considered even in the early stages of the design of a new aircraft. In classic aircraft design procedures structured by authors such as Torenbeek (1982), Raymer (2006) and Gudmundsson (2014), the engine selection occurs during the conceptual phase of the project, before parametric studies and configuration development (SEITZ, 2011), as can be seen in Figure 4.

Figure 4 - Aircraft conceptual and preliminary design process.

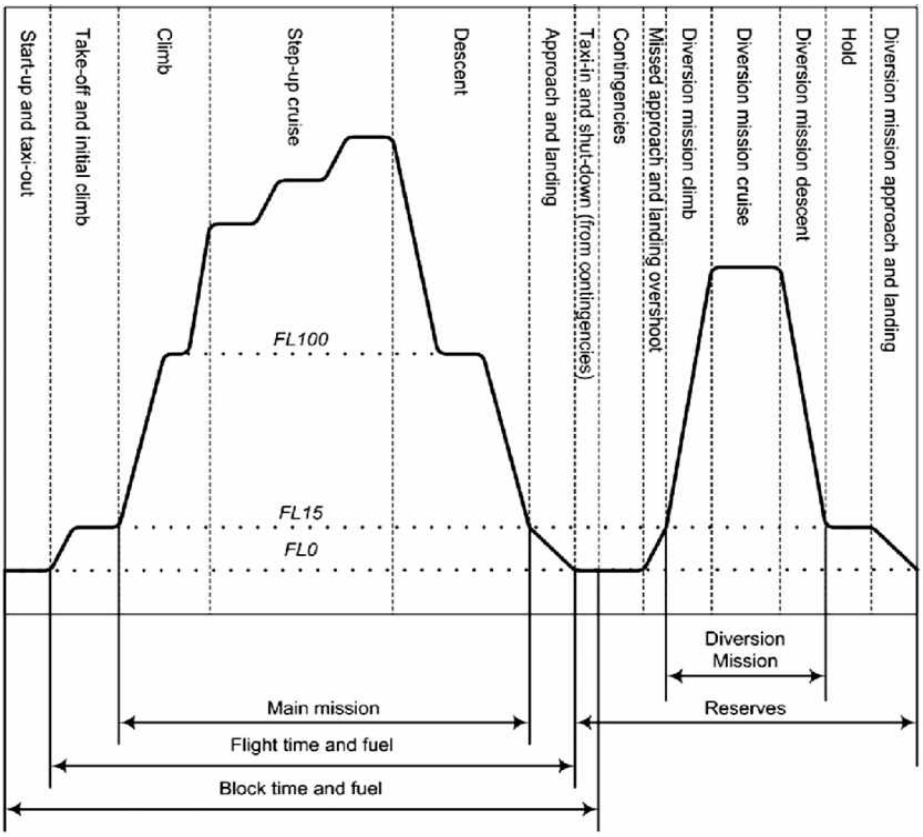


Source: according to Torenbeek (1982) and adapted from Seitz (2011).

According to Torenbeek (1982), “the type of engine suitable for a particular aircraft design is mainly determined by the following considerations: flight envelope, fuel consumption, engine weight, engine dimensions, cost, engine overhaul, and engine noise and vibration”. Consequently, it is also in the conceptual phase that the main aircraft characteristics such as type of aircraft, special aerodynamic features, mission, avionics, materials, requirements for occupant comfort, ergonomics and cost estimation are defined (GUDMUNDSSON, 2014).

However, regardless of the aircraft design procedure adopted, Oates (1989) affirms that a successful matching between aircraft and engine design occurs mainly when their performances are evaluated over their entire mission. As the mission consists of a flight path with distinct segments and well-defined characteristics, the performance requirements specific to each segment must be met not only by the aircraft, but also by the engine. A typical mission from a commercial aircraft is shown in Figure 5.

Figure 5 – Typical flight mission profile of a commercial aircraft.



Source: Xu and Grönstedt (2010).

To do this performance evaluation, the same author indicates that relationships between aircraft and power plant such as lift, drag, thrust, engine cycle characteristics and interaction or installation effects for each mission segment must be provided. Only with these relationships is possible to identify and establish performance and physical constraints indispensables in the aircraft and engine sizing (OATES, 1989).

Gudmundsson (2014) establishes these links through a physical-mathematical analysis for each flight segment of a general aircraft:

a) **Take-Off -** maneuver performed by the aircraft to reach an initial and stable climb. Highly dependent on weather conditions, the type of runway and the type and amount of landing gear. Determines the minimum thrust required to generate lift even in the event of a propulsion system failure (one engine inoperative - OEI). The runway length required for the airplane to reach the airspeed of climb, V_2, in this condition depends on thrust and is given by:

$$BFL = \frac{0.863}{1 + 2.3\Delta_{\gamma_2}}\left(\frac{W_{to}/S}{\rho g C_{L2}} + h_{to}\right)\left(2.7 + \frac{1}{\bar{T}/W_{to} - \mu'}\right) + \left(\frac{\Delta S_{to}}{\sqrt{\sigma}}\right), \qquad (01)$$

where C_{L2} is the lift coefficient at V_2, g is the gravity, h_{to} is the obstacle height (35 ft for commercial jetliners), S is the reference wing area, W_{to} the take-off weight, $\bar{T}$ is the average thrust, ρ is the air density, $\mu' = 0.01C_{L_{max}} + 0.02$, $C_{L_{max}}$ is the maximum lift coefficient for take-off configuration, ΔS_{to} is the inertia distance and equals to 655 ft, $\Delta_{\gamma_2} = \gamma_2 - \gamma_{2_{min}}$, $\gamma_2 = \sin^{-1}(T_{OEI} - D_2)/W_{to}$, $\gamma_{2_{min}}$ equals to 0.024 for 2 engines, 0.027 for 3 engines, and 0.030 for 4 engines, and D_2 is the drag at V_2. Moreover, for a jet aircraft:

$$\bar{T} = 0.75T_{to}\left(\frac{5 + BPR}{4 + BPR}\right), \qquad (02)$$

where T_{to} is the maximum static thrust and BPR the turbofan bypass ratio. On the other hand, the equation of motion during the ground run on a horizontal and flat runway is:

$$\frac{dV}{dt} = \frac{g}{W}[T - D - \mu(W - L)], \qquad (03)$$

where D and L are drag and lift, respectively, as function of V (airspeed), W is the weight and μ the ground friction coefficient. Another important take-off parameter is the Lift-off speed, V_{LOF}, generally defined as 10% higher than the stalling speed in the take-off configuration:

$$V_{LOF} = 1.1\sqrt{\frac{2W}{\rho S C_{L_{max}}}}. \qquad (04)$$

This airspeed is used to determine the thrust at Lift-off through the equation of motion.

b) **Climb –** flight segment whose objective is to gain altitude efficiently. Thus, it establishes two important indicators for the aircraft design: the ROC (rate-of-climb: indicates the rate at which the plane gains altitude), and the AOC (angle-of-climb : indicates the angle between the flight path and the ground during the maneuver). The characteristics equations of motion are:

$$L - W\cos\theta + T\sin\varepsilon = \frac{W}{g}\frac{dV_z}{dt}, \tag{05}$$

$$-D - W\sin\theta + T\cos\varepsilon = \frac{W}{g}\frac{dV_x}{dt}, \tag{06}$$

where θ is the climb angle, and ε is the angle between the x-axis (the direction of the airspeed) and the thrust. For a steady climb and $\varepsilon = 0$, the ROC, or the vertical airspeed, is defined by:

$$V_v = V\sin\theta, \tag{07}$$

Considering the same flight condition, the vertical airspeed can be also estimated as function of thrust and drag, as the Equation 08 shows for a jet aircraft:

$$V_v \equiv \frac{TV - DV}{W}. \tag{08}$$

That is, according to Equation 08, it is necessary that the thrust is greater than the drag for the maneuver to occur. In addition, considering a simplified drag model, the maximum climb angle for a jet is given by:

$$\theta_{max} \approx \sin^{-1}\left(\frac{T_{max}}{W} - \sqrt{4C_{D_{min}}k}\right), \tag{09}$$

where $C_{D_{min}}$ and k are parameters from the drag model.

c) **Cruise –** is usually the most important phase of the mission in terms of performance. The goal is to maintain a flight that is practically straight and level at an almost constant airspeed. Therefore, considering a steady motion where the angle-of-attack is small and $\varepsilon = 0$:

$$L = W, \tag{10}$$

$$D = T. \tag{11}$$

The relations expressed by equations 10 and 11 establish a series of important parameters for the design and operation of the aircraft, such as the maximum and minimum possible airspeeds (that can be estimated as function of thrust). The cruise is also linked to another major characteristic of the aircraft, responsible for selling it and defending it against its competitors: the range, that is, the distance it can cover during the flight. It can be determined by using the "Breguet" Range Equation:

$$R = \int_{W_{fin}}^{W_{ini}} \frac{V}{c_t} \frac{C_L}{C_D} \frac{1}{W} dW\ , \tag{12}$$

where c_t is the thrust specific fuel consumption:

$$c_t \equiv \frac{\dot{w}_{fuel}}{T} = \frac{dW/dt}{T}. \tag{13}$$

This formulation assumes that, during this segment of the flight, the aircraft loses weight due to fuel consumption (it is not valid for electrically powered aircraft). Moreover, its resolution depends on the type of cruise flight to be considered and the dependencies that may exist between weight, lift, and drag due to the architecture of the aircraft.

d) Descent - maneuver opposite to the climb in order to make the aircraft lose altitude. Thus, in a similar way, there are some important parameters such as: rate-of-descent (ROD), angle-of-descent (AOD), and unpowered glide distance. The equations of motions are:

$$L - W cos\theta + T sin\varepsilon = \frac{W}{g} \frac{dV_z}{dt}, \tag{14}$$

$$-D + W sin\theta + T cos\varepsilon = \frac{W}{g} \frac{dV_x}{dt}, \tag{15}$$

Considering a steady motion where the angle-of-attack is small and $\varepsilon = 0$, for a steady unpowered descent, Equations 14 and 15 become:

$$L = W cos\theta, \tag{16}$$

$$D = W sin\theta \tag{17}$$

For a steady powered descent:

$$D = T + W sin\theta \tag{18}$$

The ROD is given by:

$$V_v = \frac{DV}{W}. \tag{19}$$

e) Landing - flight phase consisting of a steady descent, a flare maneuver and a deceleration to brake the aircraft after touching the runway. Generally characterized by the approach airspeed, and as for take-off, it depends on the type of runway and the type and amount of landing gear. For a horizontal and flat runway, the equation of motion after touch-down is:

$$\frac{dV}{dt} = \frac{g}{W}\left[T - D_{l\,dg} - \mu(W - L)\right], \tag{20}$$

where $D_{l\,dg}$ is the drag as a function of V in the landing configuration and μ is the ground friction coefficient. In this case, the use of mechanical brakes is incorporated into the formulation through μ. The braking distance can be found by:

$$S_{BR} = -\frac{V_{BR}^2 W}{2g\left[T - D_{l\,dg} - \mu(W - L)\right]_{at\ (V_{BR}/\sqrt{2})}}, \tag{21}$$

where V_{BR} is the airspeed when the brakes are applied. The thrust can be positive or negative, depending on the type of engine (whether there is a reverse or not).

Once each flight segment is known and characterized, a complete mission analysis is then carried out. If the aircraft uses fossil fuel, the analysis is based on the weight loss that occurs in each segment due to fuel consumption. On the other hand, if the aircraft has completely electric propulsion, the analysis comes from the sum of the power required in each flight segment according to the speed, the drag, and the lift (GUDMUNDSSON, 2014).

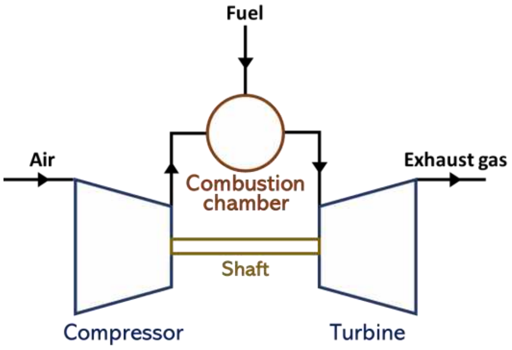
However, despite the importance of the aircraft's mission analysis for its design, the engine is generally designed or adapted to match the most critical aircraft performance requirements (TORENBEEK, 1982). Situations such as take-off with only one engine operating, minimum vertical climb speed and efficient flights at high altitudes usually determine the thrust envelope that the propulsion system must provide to the aircraft, mainly for civil application. So, once the engine design has been established for the most critical situations, the other segments of the aircraft’s mission will require only part of the installed power (OATES, 1989). This engine design/selection process in aircraft programmes is better described by Seitz (2011):

> During the feasibility phase, Top Level Aircraft Requirements (TLAR) such as payload, range, cruise speed and technology readiness at the expected entry into service date constitute the basis for the conceptual aircraft sizing yielding aircraft weights and wing area. Resulting take-off and climb performance requirements are then used to define the initial Top Level Engine Requirements (TLER). At this stage, engine manufacturers are provided with the TLER and the TLAR and propulsion system options are discussed. Trade-off studies for noise and fuel consumption are performed using component efficiencies, essential cycle parameters and bypass ratio as trade parameters. The gained trade-off results are fed back into the TLAR to ensure proper aircraft sizing. At the end of the feasibility phase, all major architectural decisions have been made and the aircraft concept including propulsion system is defined. (REMY, 2004 apud SEITZ, 2011).

The engine sizing procedure to match the aircraft requirements depends on the type of engine and may vary between manufacturers. Currently, an airplane may be equipped with the following types of power plant: piston propellers, turboprops, turbojets, turbofans, pulsejets, rockets, and electric motors (GUDMUNDSSON, 2014). However, those based on a gas turbine (turboprops, turbojets, and turbofans) are the most used, whereas piston engines are only used on very small aircraft.

A gas turbine engine produces power or in the form of shaft power or in the form of an exhaust jet, and then converts that power into thrust through a propeller or a jet nozzle, respectively (OATES, 1989). A simple model of a gas turbine is shown in Figure 6.

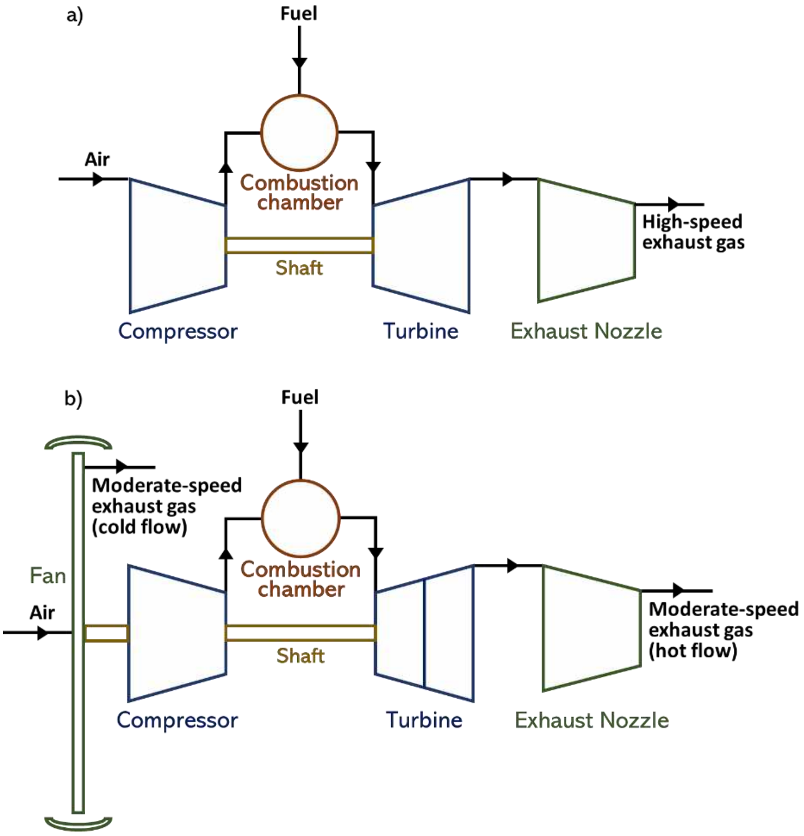
Figure 6 – Simple gas turbine model.

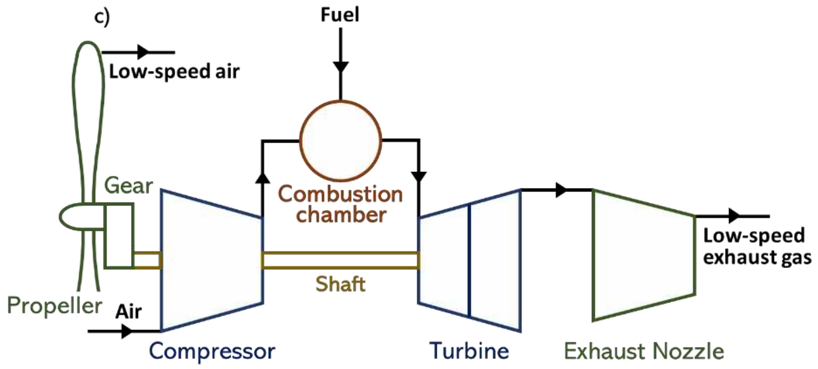


Source: adapted from Saravanamuttoo, Rogers, and Cohen (2001).

From this basic model, several components can be added in order to configure the engine in different ways, as can be seen in Figure 7. Each configuration has its own characteristics and, therefore, are indicated for different types of aircraft (Chart 2). As well as their characteristics, their design parameters also vary according to the configuration, since the kinetic and thermodynamic relationships that are established between the components vary (HILL; PETERSON, 1992).

Figure 7 – Turbojet (a), turbofan (b), and turboprop (c) models.





Source: adapted from Hill and Peterson (1982).

Chart 2 – Gas turbine engines applications.

Gas Turbine Engine	Aviation application
Turboprop	indicated for low flight speeds (inefficient and noisy for speeds above Mach 0.5 - Mach 0.6).
Turbofan	efficient and quiet for high flight speeds (Mach 0.85).
Turbojet	normally used for supersonic flights (military aircraft).

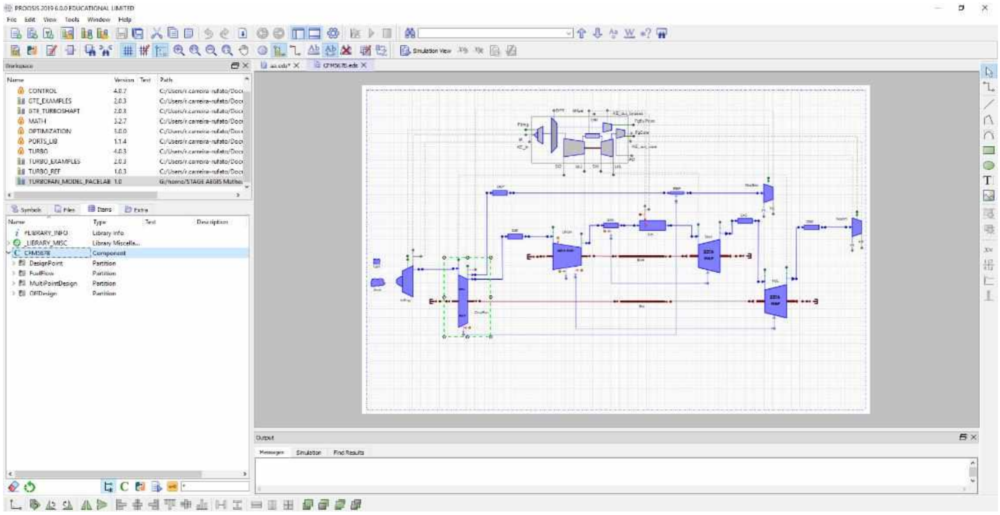
Source: adapted from Hill and Peterson (1992).

Thus, except for electric motors, the engine sizing can be also interpreted as a thermodynamic analysis that must be conducted for each engine component at all flight conditions (HILL; PETERSON, 1992). Indeed, the engine performance in these cases depends largely on its thermodynamic characteristics, as is discussed by Oates (1989), Hill and Peterson (1992). Parameters such as airflow rate, compression ratio, and gas temperature at the turbine inlet are essential to size the engine in order to produce the necessary power for a specific condition (OATES, 1989).

2.2 Engine and Aircraft Simulation Tools

To assist in the aircraft and engine design at the conceptual phase and perform performance calculations some analytical, numerical, and empirical tools can be used. For the simulation of the propulsive system, the usual found tools are based on the operation of gas turbines. An example is PROOSIS, Figure 8, an object-oriented simulation software for propulsion that was developed by the European project VIVACE-ECP (Value Improvement through a Virtual Aeronautical Collaborative Enterprise - European Cycle Program) (BALA et al., 2007). The application allows the user to create mathematical models of a physical propulsive system and to solve complex numerical problems related to it. PROOSIS is programmed using a high-level language called EL, developed from C++ with all the capabilities of an object-oriented programming language (ALEXIOU; TSALAVOUTAS, 2011).

Figure 8 – PROOSIS Interface in Schematic View.



Name	Version	Test	Path
CONTROL	4.0.7		C:/Users/r.carreira-rufato/Doc
GTE_EXAMPLES	2.0.3		C:/Users/r.carreira-rufato/Doc
GTE_TURBOSHAFT	2.0.3		C:/Users/r.carreira-rufato/Doc
MATH	3.2.7		C:/Users/r.carreira-rufato/Doc
OPTIMIZATION	5.0.0		C:/Users/r.carreira-rufato/Doc
PORTS_LIB	1.1.4		C:/Users/r.carreira-rufato/Doc
TURBO	4.0.3		C:/Users/r.carreira-rufato/Doc
TURBO_EXAMPLES	2.0.3		C:/Users/r.carreira-rufato/Doc
TURBO_REF	1.0.3		C:/Users/r.carreira-rufato/Doc
TURBOFAN_MODEL_PACELAB	1.0		G:/home/STAGE AEGIS Mathe

Name	Type	Test	Description
#LIBRARY_INFO	Library Info		
_LIBRARY_MISC	Library Miscella...		
CFM567B	Component		
DesignPoint	Partition		
FuelFlow	Partition		
MultiPointDesign	Partition		
OffDesign	Partition		

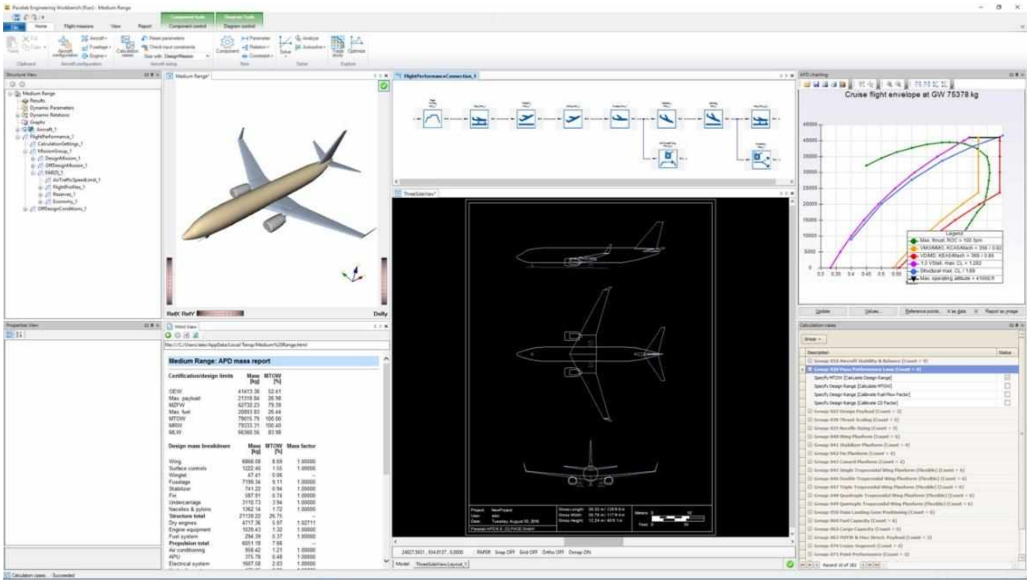
Source: the Author.

The capabilities of PROOSIS are described by Bala et al. (2007) and include high fidelity, distributed computing architecture, multidisciplinary optimization capability, and steady state design performance and off-design performance simulations. Another advantage described by the author is the flexibility regarding data visualisation, since PROOSIS can generate decks that can be used by other users for off-design performance studies to evaluate the engine behaviour for a flight envelope (ALEXIOU; TSALAVOUTAS, 2011).

Regarding the simulation of an aircraft, several software solutions for the initial stages of the project were developed in the last years (SEITZ, 2011). Amongst them Pacelab APD (Aircraft Preliminary Design) is highlighted, where the aircraft design calculation refers to handbook methods, particularly Torenbeek (1982) and Raymer (2006). The application, as seen in Figure 9, allows manufacturers and research institutions to set up multidisciplinary analysis methods for aircraft modelling, sizing, and optimization, focusing on obtaining reliable data to enable a strategic project management (SCHNEEGANS, 2012).

Among the capabilities of this tool, there is the possibility of a detailed evaluation of conventional and advanced airplanes configurations, allowing, even at the early stages of the design process, the visualization of the impact and risk that new techniques and conceptual innovations bring to the project. In addition, Pacelab APD its open software architecture (SCHNEEGANS, 2012).

Figure 9 – Pacelab APD interface.



Source: TXT GROUP (2020).

It is possible to find in the literature several cases were other tools where used to improve or to complete the analysis performed by Pacelab. Schneegans (2012), uses an additional database from a general engine deck in order to investigate novel systems architectures at the aircraft level in Pacelab. In the same way, Gologan, Schmitt, and Luftfahrt (2010) use propulsive systems models provided by GasTurb, a software equivalent to PROOSIS, to conduct comparative analysis of powered-lift turbofan aircraft with conventional turboprop aircraft for extreme short take-off and landing applications. There are also cases where propulsive models provided by other simulation software, Numerical Propulsion System Simulation (NPSS), are used with Pacelab SysArc, software that uses the base design provided by Pacelab APD for the complete structuring of aircraft systems, to the conception of aeronautical projects with new propulsive architectures (CHAKRABORTY et al., 2014; CHAKRABORTY et al., 2015).

Another example is developed by Fefermann et al. (2018), where an engine model generated by PROOSIS is used by Pacelab APD for the study of several propulsive configurations in an aircraft. However, it is not mentioned by the authors as the PROOSIS model was used in the simulations made by Pacelab APD.

3 DEFINITION OF THE COUPLING ROUTINE

This chapter defines the objectives of this study, investigates coupling possibilities, and creates the simulation models.

3.1. Problem Statement

The focus of this project is to establish a coupling routine between the PROOSIS and Pacelab APD computational tools in order to improve the simulations done by them and, consequently, to improve the conceptual design process of an aircraft. After all, it is known that improvements in simulation lead to increased prediction accuracy while decreasing in time and cost (NASA, 2015).

Thus, this study focuses on obtaining a routine that better integrates the propulsive system to the other aeronautical systems, allowing to achieve a more accurate representation of the interactions that occur within a complex architecture such as an aircraft (SEITZ, 2011). However, as described by Silva et al. (2015), the integration of computational systems creates a System of Systems that has a high probability of being unstable. So, to find a consolidated and stable coupling is intended, by employing as many interactions between systems as possible.

Therefore, based on the cases studied in the literature review, the objectives of this study are:

a) to analyse the coupling possibilities to identify the relevant variables for the information exchange between the two pieces of software.
b) in the sense of a one-way communication, from PROOSIS to Pacelab APD, to manually incorporate the engine performance data in order to determine a coupling routine.
c) to Identify ways to implement more automated couplings, also considering bilateral communication between the applications.

3.2. Primary analysis of coupling possibilities

Pacelab APD is programmed by using C#, an object-oriented programming language. Its original architecture is exposed to the user through the Pacelab APD

Knowledge Designer interface, where it is possible to access all the mathematical and logical procedure that determines the operation of the program.

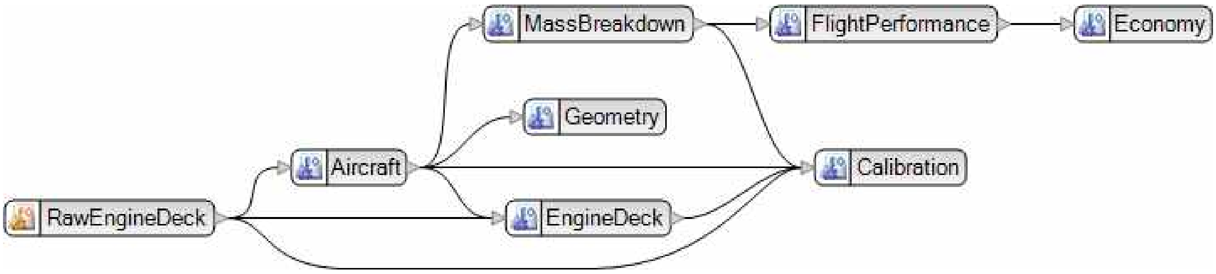
Taking advantage of its open architecture, the first step was to analyse existing modelling, scaling, and optimization methods to identify which parameters and variables related to the engines are used, how they are used and where they are allocated in the software architecture.

Since the propulsive system is of essential importance for the operation of an aircraft, as seen in Chart 1, it is subjected to numerous interactions with other aircraft systems. This is naturally translated and found in the various calculation methods, making the impact zone of the propulsion system in the program architecture enormous. Inevitably, to connect all these objects and functions to an external element would be difficult because it would be necessary to change much of the code of the program.

However, it has been observed that Pacelab APD uses a database for the resolution of many of its methods. Indeed, regarding the engine, there is no internal process of detailed simulation of its operation. The program performs the calculations of sizing and performance of the engine mainly from performance data already present in its database. In addition, the options provided by the application for incorporating other commercial tools, as mentioned in the second chapter, are translated into the propulsion system as a tool for importing its performance data.

Such imports are carried out through the Raw Engine Deck tool whose operating principle is also accessible and manipulative through the Pacelab APD Knowledge Designer. In fact, its processes of data reading, data identification and storing, are easily accessible and the engineering objects and functions related to the tool are known, as seen in Figure 10.

Figure 10 - Engineering objects and functions objects related to the Raw Engine Deck.



Source: the Author.

Since Pacelab already contains an integration method implemented and consolidated, and due to the software's nature by using performance tables for the engine simulation, it was decided to implement the incorporation of performance tables generated by PROOSIS as a first approach to the coupling. Undoubtedly, Pacelab APD is a program focused on the initial stages of aircraft design, aiming to provide a reliable basis of information for the development of the rest of the project. Therefore, for these preliminary design phases, the use of performance tables may be enough, since this stage of the project focuses on obtaining qualitative data that model aircraft behaviour through trend studies.

Pacelab APD has scalable performance tables for six reference engines, including five turbofan models and one turboprop model. These models were obtained from methods described by Torenbeek (1982) and Raymer (2006) based on the technology available at the end of the 20th century and at the onset of the 21st century. The reference thrust values are shown in Table 1. With the aid of calibration factors, the application scales each performance table from the reference thrust. Therefore, what there is when creating a new engine, is a modification of the performance tables for a given type of engine through a multiplicative factor.

Table 1 – Reference thrusts of Pacelab APD engine models.

Engine model	**Thrust**
Default-large	80000 lbf
Default-medium	40000 lbf
Default-small	20000 lbf
Turboprop	2750 shp
Augmented-large	30000 lbf
Augmented-small	7500 lbf

Source: the Author.

The performance tables are divided into two groups:

1) Rating thrust: Maximum Take-off, Maximum Climb, Maximum Cruise, Maximum Continuous, Idle Thrust. Chart 3 summarizes the characteristics of each rating thrust.
2) Fuel-flow: Idle and Non-Idle.

Chart 3 – Rating thrust characteristics of an engine.

Rating Thrust	Characteristics
Maximum Take-off	maximum thrust available for take-off. This rating is usually limited to 5 minutes due to limitations imposed by the maximum temperature allowed at the turbine inlet.
Maximum Climb	maximum thrust that can be used during normal climb operations, usually limited to 30 minutes.
Maximum Cruise	maximum thrust available for cruise.
Maximum Continuous	maximum rating that can be used continuously. Intended to be used during an emergency such as one engine inoperative.
Idle	thrust rating usually determined by minimum fuel flow or shaft rotational speed requirements (to power other systems).

Source: Torenbeek (1982), Oates (1989) and Gudmundsson (2014).

Moreover, the parameters of these tables are deviation temperature of ISA condition, altitude, flight Mach, thrust and fuel consumption. So, these were considered the base variables necessary for the import of an engine performance model from PROOSIS to Pacelab APD.

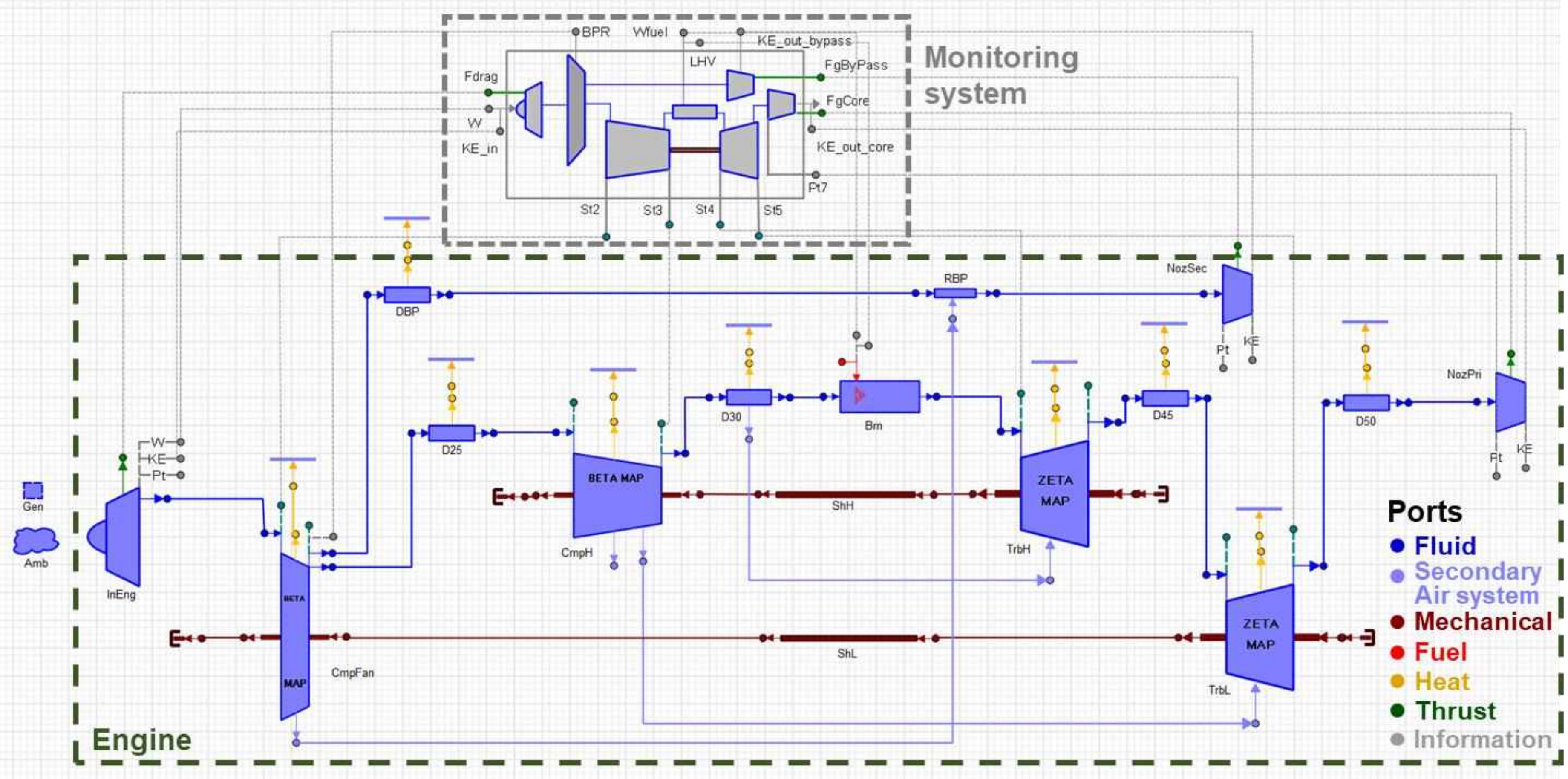
3.2.1 Engine Model

To obtain performance data, it was necessary to establish an engine model and implement it through PROOSIS. Due to its extensive use in current commercial aviation, a two-spool turbofan was chosen for an unmixed flow case already embedded by the library of the application itself. It is a very close representation of a real example, despite the complexity of propulsions systems. Chart 4 and Figure 11 indicate the components and the engine model, respectively. The numbers in the labels and variables refer to the plans along a turbofan engine (see Annex A). Also, each port is responsible for connecting its characteristic variables between the engine components, following the direction of its arrows.

Chart 4 – Engine model components.

Component	Label	Characteristics
General	**Gen**	sets the fluid model of the simulation and provides its thermodynamic properties.
Atmosphere	**Amb**	provides ambient conditions and the Mach number at the engine inlet.
InletAtm	**InEng**	simulates the inlet nozzle of a typical gas turbine through calculation of flow conditions, momentum drag and the flow kinetic energy for given inlet conditions and other performance parameters.

Figure 11 – PROOSIS two-spool turbofan model.



Source: the Author.

Component	Label	Characteristics
Fan **BETA MAP**	**CmpFan**	derives the flow conditions at the core and the bypass, considering the constraints imposed by a performance map and an air bleed.
Duct	**DBP, D25, D30, D45, D50, RBP**	simulates the operation of any duct between engine components, with and without air bleed.
Compressor **BETA MAP**	**CmpH**	predicts compressor operation, considering the constraints imposed by a performance map and air bleed.
Shaft	**ShH, ShL**	Connects two rotating components by transferring torque and speed.
Burner	**Brn**	simulates the operation of a gas turbine burner.
Turbine **BETA MAP**	**TrbH, TrbL**	calculates the flow conditions and produced power for given inlet conditions and characteristic performance parameters, considering the constraints imposed by a performance map.
Nozzle	**NozSec, NozPri**	derives the mass flow rate that passes through the nozzle, assuming adiabatic and isentropic flow.

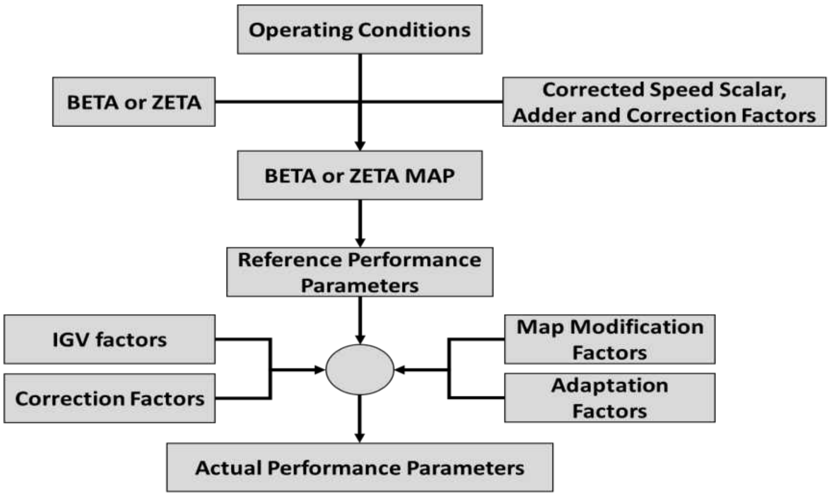
Source: Alexiou and Tsalavoutas (2011).

As shown in Chart 4, some mechanical components used (fan, compressor, and turbine) have integrated performance maps which predict their design and off-design operation (ALEXIOU; TSALAVOUTAS, 2011). Unquestionably, to carry out the simulation, the combination of two different analyses is necessary:

1) design point performance calculation for the design of the engine to a fixed operating condition.
2) off-design cycle to predict engine performance for a flight envelope.

The analysis of the mathematical model behind the use of performance maps is complex and goes beyond the objectives of this study. However, its principle of use by the software during engine performance simulation is shown in Figure 12.

Figure 12 – Use of performance maps by PROOSIS in engine simulation.



Source: adapted from Alexiou and Tsalavoutas (2011).

3.2.2 Engine Sizing

In order to carry out the engine sizing and then to perform a mission analysis, it was necessary to use data from a known engine. The CFM56-7B27 engine, which powers the Boeing 737-800, was chosen because there is a comprehensive literature on the use of turbofans in commercial aircraft for research. Thus, the assignment of values to the boundary variables selected by the software could be made using data provided by the literature and the manufacturer.

As a first approach, it was decided to design the engine only for a critical flight point: the take-off. Indeed, according to Torenbeek (1982), the "design point is intended to indicate the working condition at high rpm where the efficiencies of the compressor and turbine are optimum". Although the same author indicates that other conditions at high altitudes can also be critical, depending on the type of the engine, the take-off clearly expresses extreme temperature requirements at high shaft rotational speed for the engine thermodynamic cycle (GUDMUNDSSON, 2014).

On PROOSIS, the engine sizing is made from a design partition where all the design parameters are chosen by the user. However, the parameters used were suggested by Alexiou and Tsalavoutas (2011) and are shown in Table 4 (see section 3.3). As discussed previously, a part of boundary variables used, and their values, comes from the literature, whereas the remaining variables are already incorporated in the model provided by the library and was not changed. They are all described in the Table 2.

Table 2 – Boundary variables used.

Variable	Value	Description
CmpFan.BETA	0.6	CORE BETA parameter
CmpFan.Beta_sec	0.6	BYPASS BETA parameter
BPR	5.1	Fan bypass ratio
CmpFan.NcRdes	0.8	Design rotational speed CORE
CmpFan.NcRdesMap	0.8	Design rotational speed CORE
CmpFan.NcRdesMap_sec	0.8	Design rotational speed BYPASS
P21Q2	1.6	Compressor work PR
P13Q2	1.6	Fan bypass work PR
EP21	0.9	Polytropic efficiency
EP13	0.9	Bypass fan polytropic efficiency
CmpH.BETA	0.5	BETA parameter

Variable	Value	Description
NH	14460 rpm	Rotational Speed
NL	5175 rpm	Rotational Speed
CmpH.NcRdes	0.8	Corrected rotational speed
CmpH.NcRdesMap	0.8	Corrected rotational speed
P3Q25	20.4375	Compressor work PR
EP3	0.9	Polytropic efficiency
W1	354 kg/s	Inlet mass flow rate
TrbH.NcRdes	0.95	Relative corrected speed
TrbH.NcRdesMap	0.95	Relative corrected speed map value
Tt41	1650 K	Total temperature
TrbH.ZETA	0.5	Map auxiliary coordinate
EP43	0.9	Polytropic efficiency
TrbL.NcRdes	0.9	Relative corrected speed
TrbL.NcRdesMap	0.9	Relative corrected speed map value
TrbL.ZETA	0.5	Map auxiliary coordinate
EP5	0.9	Polytropic efficiency

Source: Guynn et al. (2009), and EUROPEAN AVIATION SAFETY AGENCY - EASA, (2016).

The mathematical calculations and the thermodynamic analysis necessary for the engine sizing and performance simulation performed by PROOSIS are based mainly on the work of Walsh and Fletcher (2004) (ALEXIOU; TSALAVOUTAS, 2011). As the level of complexity and detail of these analyses is beyond the scope of this work, the equations and methods used by the software will not be presented. However, if desired, they are available for consultation in its documentation, which was frequently consulted during this project.

3.2.3 Off-design engine performance

Once the sizing was done, to simulate the operation of the engine during the flight phases it was also necessary to define a variable as a boundary condition. The solution naturally employed by PROOSIS is to use the fuel flow injected into the combustion chamber. In fact, this is one of the real parameters that can be manipulated by the pilot.

However, what was intended to obtain in terms of performance table was the performance of the propulsive group for flight limit conditions, having the thrust and the fuel flow as output values of the simulation. Indeed, in this first approach routine, a replacement of the performance tables used by Pacelab APD was intended (see section 3.2).

Thus, the choice of fuel flow or thrust as a boundary condition determines that their values are specified for the simulation. Therefore, choosing these variables as simulation input precludes obtaining the maximum engine performance data as output, since such values have already been specified at the beginning.

It was necessary then to use another parameter as simulation input that translated the maximum conditions of the engine operation. According to Dupont (2010), the Maximum Climb and Maximum Cruise conditions can be interpreted for the engine as 98% and 96% of the nominal rotation speed of the compressor axis, respectively, considering the take-off condition as nominal speed. Such association is also made by Torenbeek (1982) who indicates a limit in the rotational speed for climb and cruise conditions for a four stroke Otto-type engine. Moreover, Boyer (2017) affirms that the maximum rotational speeds of the high-pressure and low-pressure shafts are some of the parameters chosen to limit the turbofan engine operation.

Indeed, for a gas turbine engine some of the ratings thrust are defined by turbine entry temperature evolution (TET) laws as a function of altitude, Mach number, and deviation temperature of ISA condition (BOYER, 2017). However, as discussed by Laskaridis (2004), the TET and the rotational speed of the high-pressure shaft have a direct relationship with each other. In fact, according to Martin (2009), small changes in the shaft speed can cause significant increases in temperature: an increase of 2% in speed above the design limit may result an increase of 50 K in TET.

The importance of the rotational speed of the shafts is so great that, in addition to being constantly monitored, their measurement plays a fundamental role in controlling the engine power (LUTAMBO et al., 2015; PRENCIPE, 2000; BOYER, 2017; MARTIN, 2009). Thus, to carry out the simulation of maximum engine performance, the rotation speed of the compressor axis was chosen as boundary variable.

It should be emphasized that it is not the purpose of this research to reproduce with the maximum of details all the control interactions that may exist between the cockpit and the propulsive system, since the virtual engine model used is already a reduced model. Moreover, such approach would require an expertise that is very restricted to engine and aircraft manufacturers and would exceed the initial objectives of developing a coupling method that is effective for the preliminary phases of the aircraft design.

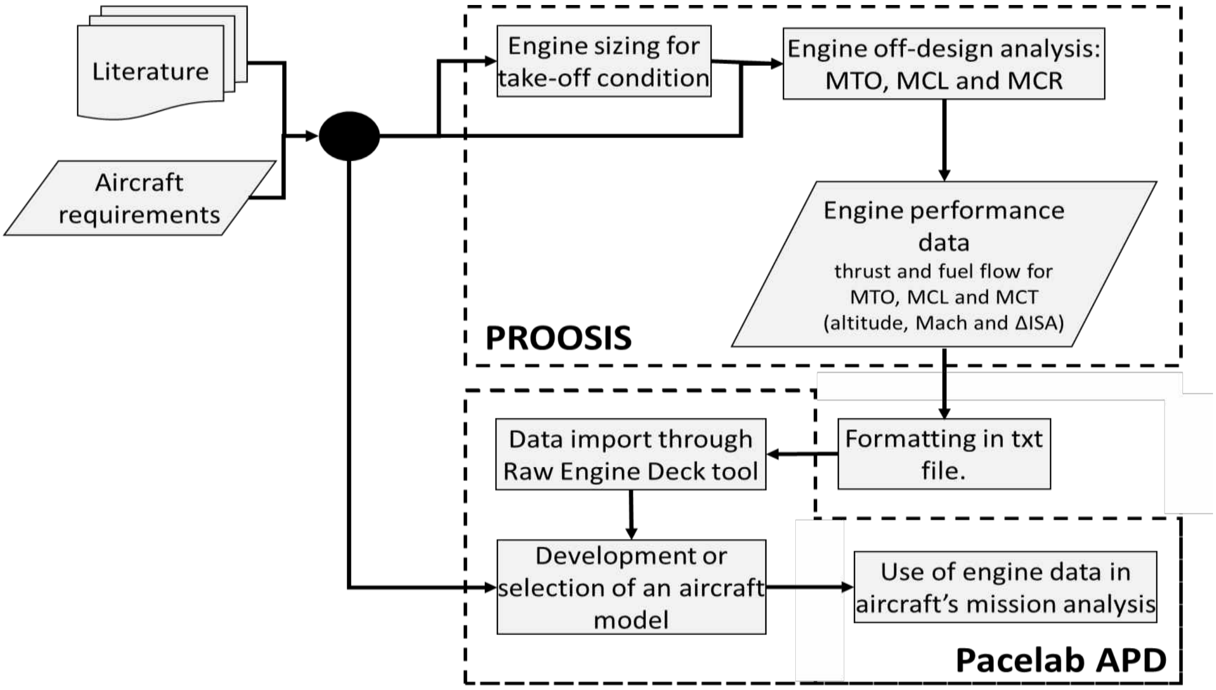
Finally, the simulation procedure adopted for the different maximum working conditions was to carry out a parametric study that, based on the engine sized and the maximum rotational speed of the compressor, established their maximum thrusts and their fuel consumption.

The convergence criterion chosen for the simulations was FRACTOL, a local residues calculation criterion of PROOSIS more appropriate to cases when the value of the calculated variable is very high or very low. For the other numerical simulation parameters, the standard values automatically specified by PROOSIS were used.

3.2.4 Results of the first coupling routine

Performance tables for MTO, MCL and MCR were obtained and imported to Pacelab APD through the “Raw Engine Deck” tool by using .txt files. This first coupling routine is synthesized in Figure 13.

Figure 13 – First coupling routine between PROOSIS and Pacelab APD.



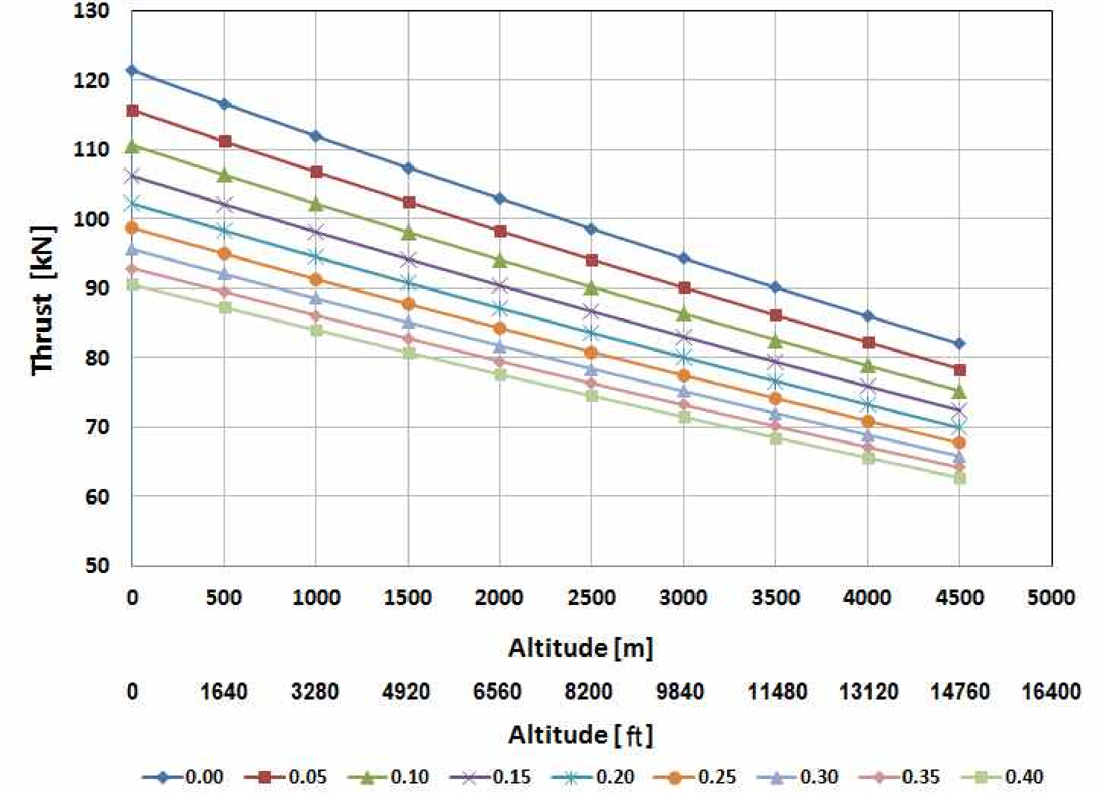
Source: the Author.

For maximum take-off, data were obtained for flight Mach ranging from 0 to 0.40 at altitudes from 0 to 4 500 m, considering four deviations temperature of ISA condition: 0 K, +5 K, +10 K and +15 K. Graphic 1 shows the thrust values obtained for take-off conditions at 0 K, i.e., in ISA condition.

For maximum climb and maximum cruise, the data obtained refer to flight Mach ranging from 0 to 0.82 (maximum Mach number allowed for Boeing 737-NG) at altitudes ranging from 0 to 11 250 m. Graphic 2 and Graphic 3 show the thrust values obtained for MCL and MCR at ISA condition, respectively. It can be seen in these graphics that the model used, sized only for take-off, was not able to find results for thrust at high altitudes, mainly above 10 000 m (~ 33 000 ft).

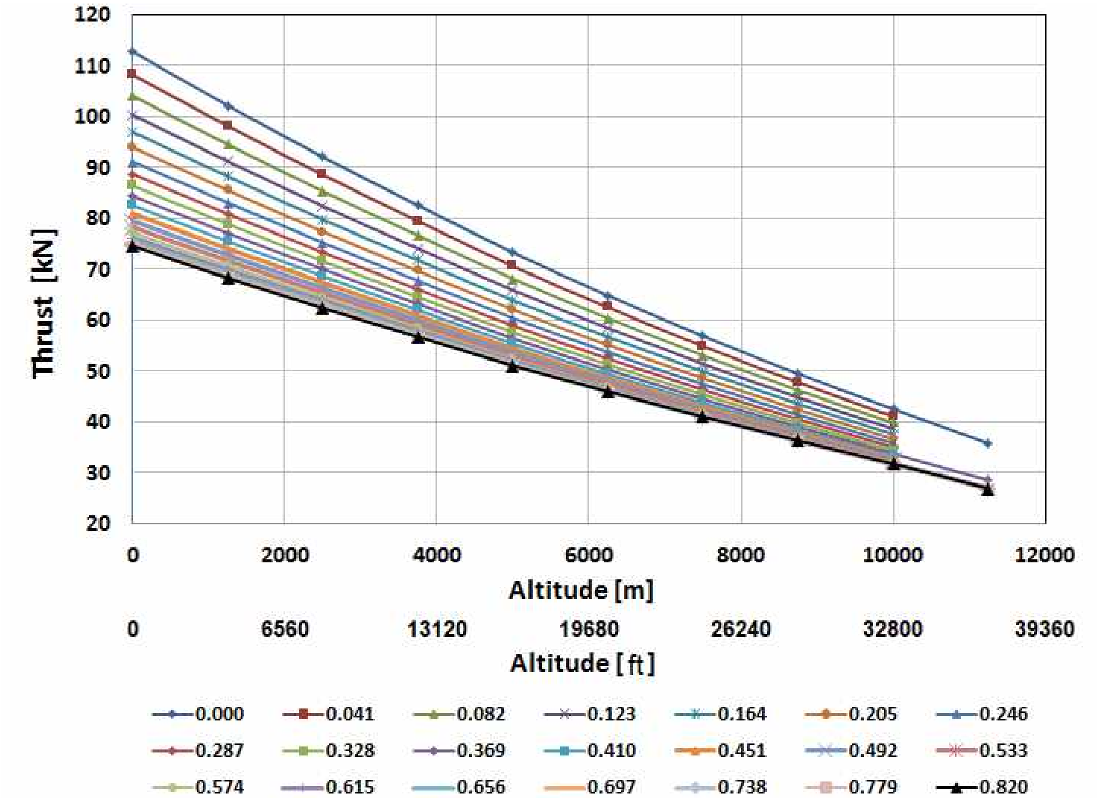
Since not enough information was found in the literature that could clearly establish the operating conditions that define the maximum continuous and idle ratings thrust, it was not possible to obtain a performance data for these cases. In this first coupling routine, no specific simulation to investigate fuel consumption was performed. Indeed, its main objective was to explore the import of data and analyse its impacts in the analysis of the aircraft's mission.

Graphic 1 - MTO engine thrust at ISA +0 K in PROOSIS.



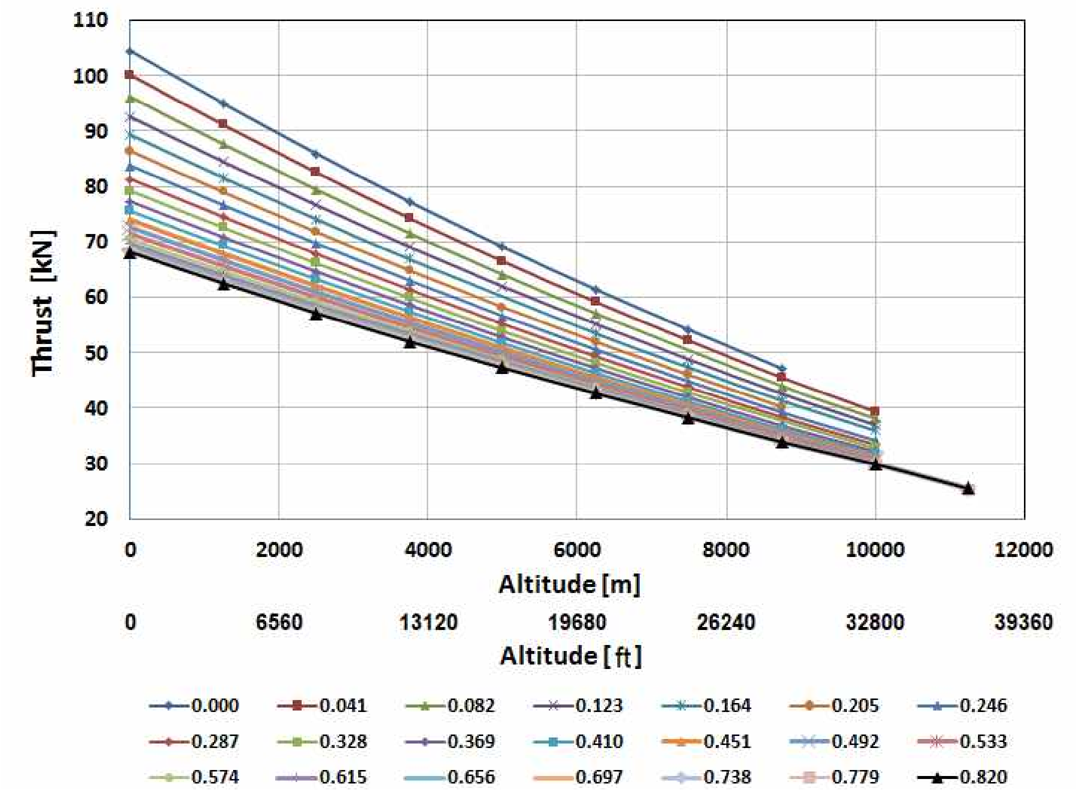
Source: the Author.

Graphic 2 - MCL engine thrust at ISA +0 K in PROOSIS.



Source: the Author.

Graphic 3 - MCR engine thrust at ISA +0 K in PROOSIS.

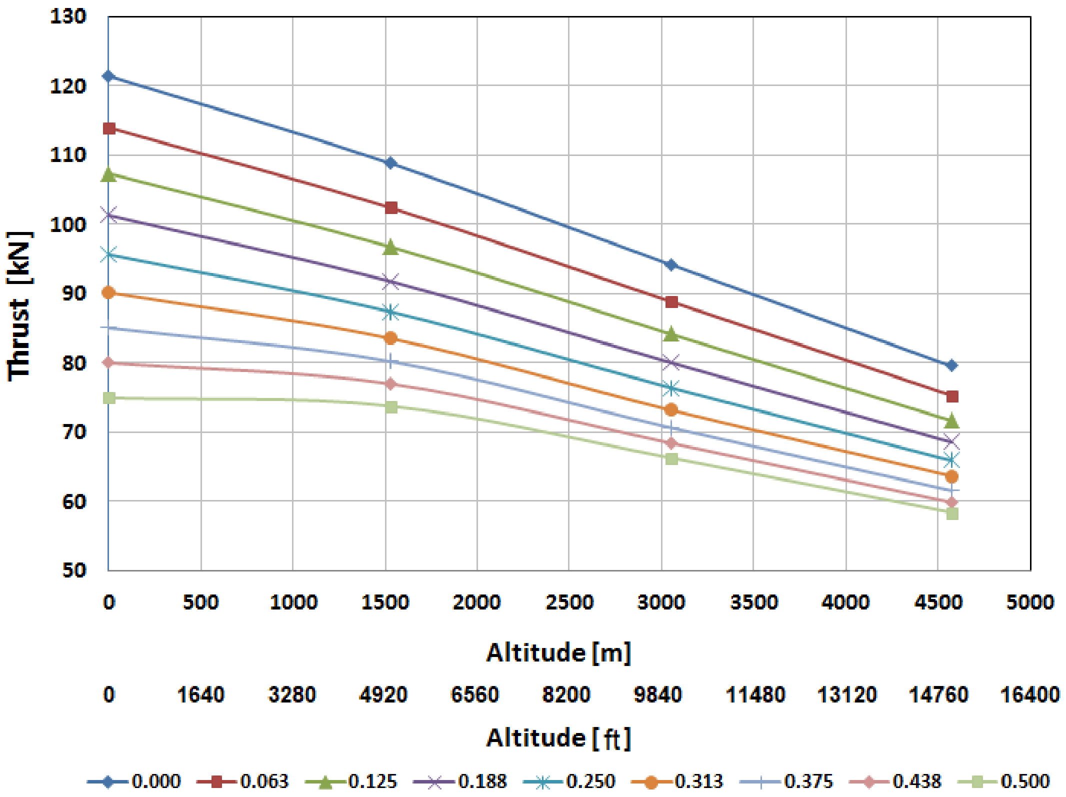


Source: the Author.

These data can be compared with the existing performance tables in Pacelab APD and used for the Boeing 737-800 design, which is also available in the application. The tables used by the tool for this aircraft represent an expansion of the default-small engine data for a reference thrust of 121436 N and are represented by the graphics shown in Graphics 4, 5 and 6. A different behaviour in the curves is observed between the performance data for all flight conditions examined, mainly above a flight Mach of approximately 0.5.

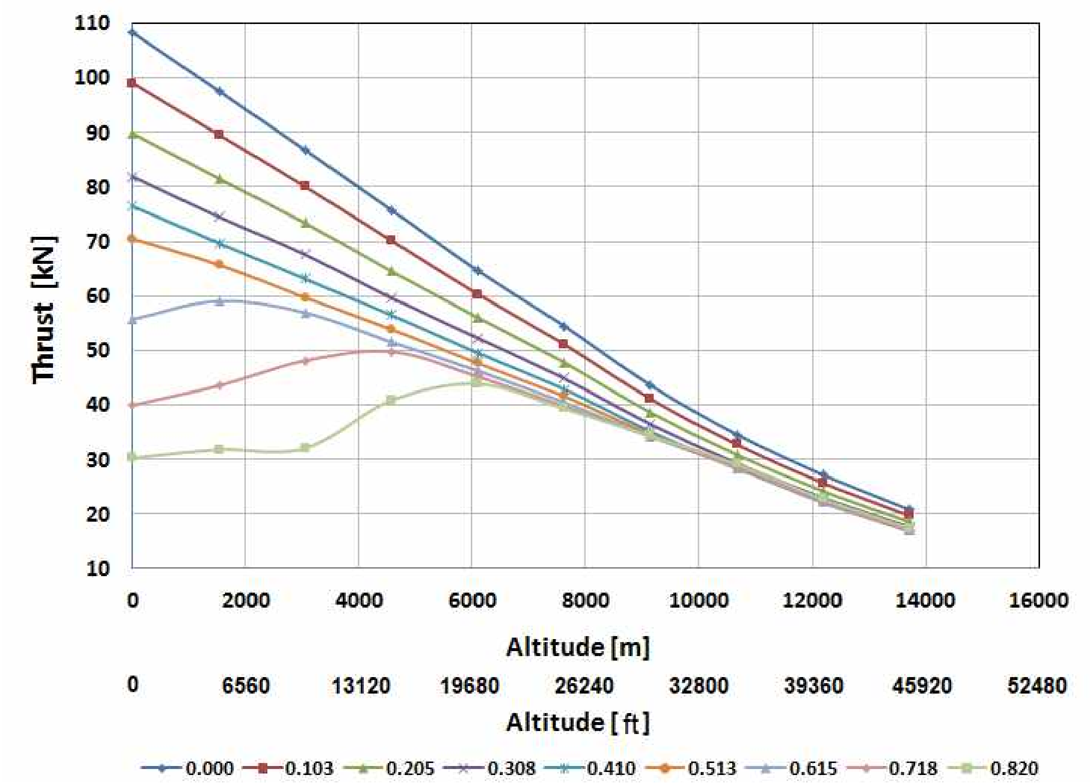
According to the scarce information provided by the software's owner concerning the engine data, these values are obtained from manual methods, probably from approximations and physical and mathematical considerations that cannot accurately describe the operation of the engine. Actually, as shown in Table 3, the Boeing 737-800 design available in Pacelab APD cannot achieve its real range, considering this engine data. However, even the simulated data imported from PROOSIS to the software were not able to cause a significant change in the aircraft range.

Graphic 4 - MTO engine thrust at ISA +0 K. Default-small (Pacelab APD model).



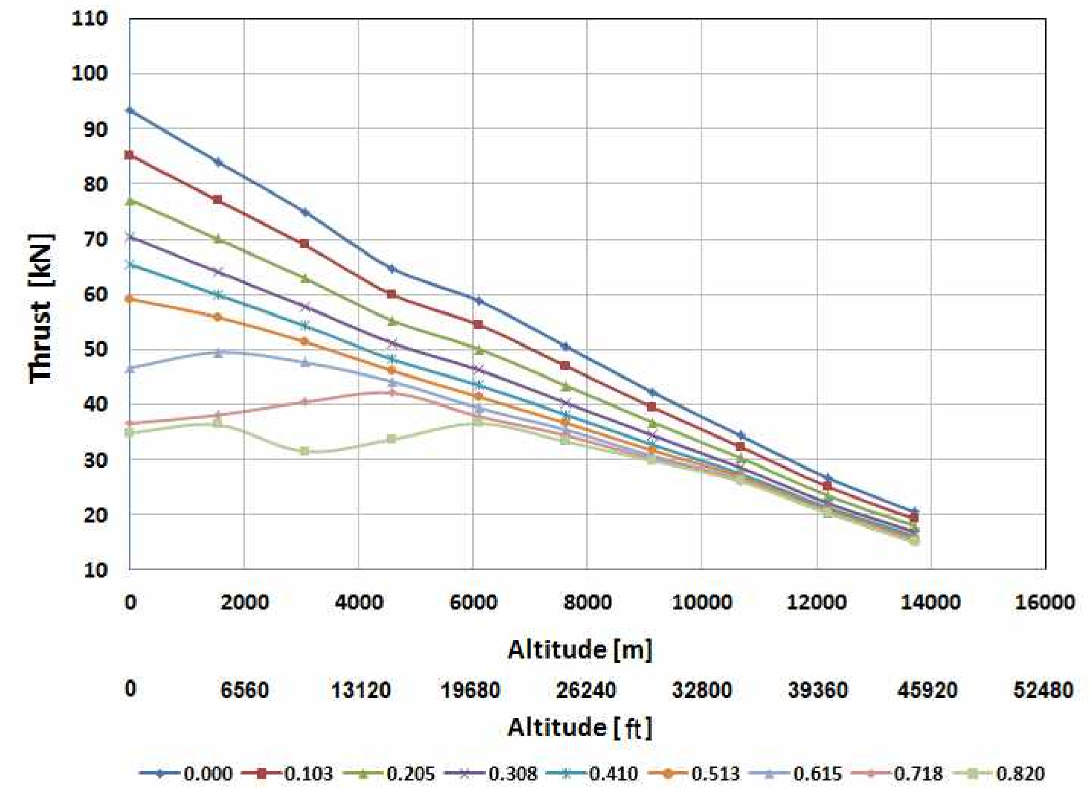
Source: the Author.

Graphic 5 - MCL engine thrust at ISA +0 K. Default-small (Pacelab APD model).



Source: the Author.

Graphic 6 - MCR engine thrust at ISA +0 K. Default-small (Pacelab APD model).



Source: the Author.

Table 3 – Range of each model.

Engine model	Range
Pacelab model	5 149 km
PROOSIS model	5 152 km
Real engine	5 665 km

Source: the Author.

This first coupling routine might not have been able to reproduce the real model in terms of range for several reasons:

a) the mission profile of the models may be different from that used for the real aircraft, mainly in the type of cruise considered.

b) the import of all performance tables necessary for the project was not carried out. In fact, no simulation was done for Idle condition and fuel consumption. Therefore, the same default-small engine data was used for these regimes.

c) the simulations performed presented problems of convergence for all flight speeds from an altitude of 10 000 m. Thus, simulated data is missing for some of the MCL and MCR regimes. Indeed, engine sizing was done only for a single point, the take-off, and, as shown in Figure 3, the ability of max climb at high altitudes is also a key design point (SEITZ, 2011). In addition, according to Torenbeek (1982), in high bypass engines the cruise working condition is also a critical point. To correct this error, it is necessary then to perform a multi-point design, that is, to size the engine for all critical phases of flight.

d) as standard performance data simplify the actual performance of an engine, the other data and methods used for the rest of the aircraft, especially for aerodynamics, can share the same principle of simplification, resulting in a design that is naturally different from the real aircraft. However, such questions go beyond the objective of this research, due to the focus on the propulsive system.

Therefore, to achieve better results, it was necessary to rethink the coupling routine, mainly in the engine sizing and its off-design analysis. However, despite the problems, this first procedure was important to identify the necessary variables for a coupling between the two pieces of software. Moreover, this coupling is intended to a user who possesses enough technical knowledge for the design of the propulsion system, making possible any simulation problems related to the engine sizing and operation can be easily corrected.

3.3 Improving the coupling routine

As indicated in section 3.2.4, to achieve better results, some improvements on the coupling routine had to be made. These improves are discussed in the following sections.

3.3.1 Engine design changes

As previously identified, for gas turbine engines it is necessary to make an sizing for at least two distinct phases of flight: take-off and end-of-climb, since the sizing just for take-off turned out an unsatisfactory model for the calculation of propulsive performance at high altitude (> 10,000 m or > 30,000 ft). So, it was decided to size the engine for take-off, end-of-climb, and cruise in order to create a model as efficient as possible, mainly during the cruise simulation.

Using the same engine model (see Figure 11 and Chart 4), it was established on PROOSIS a Default Partition, called *MultiPointDesign*, having the thrust as boundary variable. This choice is due the fact that this variable can be found in the literature for the three flight points mentioned.

To conceive the design for several flight points, it was necessary to launch an Extended Steady calculation through a Wizard Experiment in Default Partition. The design parameters chosen were the same used for the sizing done previously. Also, they were initialized with the values obtained by the previous model to accelerate the calculation. For the input data of the design points, it was chosen the altitude, the Mach number, and the ISA temperature deviation. All variables and parameters can be found in Table 4 and Chart 5.

Table 4 – Parameters used in the engine design.

Data	Initial Value	Description
A18	0.869893933 m^2	Exit plan area (Bypass)
A8	0.216838308 m^2	Exit plan area (Core)
CmpFan.NcDes	5712.5549 rpm	Design corrected speed
CmpFan.s_NcRdes_pri_in	1.39285714	Corrected rotational speed scalar (Core)
CmpFan.s_NcRdes_sec_in	1	Corrected rotational speed scalar (Byp.)
CmFan.s_mapEff_pri_in	1.12152316	Isentropic efficiency scalar (Core)

Data	Initial Value	Description
CmFan.s_mapEff_sec_in	1.03853807	Isentropic efficiency scalar (Bypass)
CmFan.s_mapPR_pri_in	3.63709575	Pressure ratio scalar (Core)
CmFan.s_mapPR_sec_in	1.48283971	Pressure ratio scalar (Bypass)
CmFan.s_mapWc_pri_in	1.57069324	Corrected mass flow rate scalar (Core)
CmFan.s_mapWc_sec_in	0.75920195	Corrected mass flow rate scalar (Bypass)
CmpH.NcDes	17775.5388 rpm	Design corrected speed
CmpH.s_NcRdes_in	1	Corrected rotational speed scalar
CmpH.s_mapEff_in	1.01424378	Isentropic efficiency scalar
CmpH.s_mapPR_in	4.79672486	Pressure ratio scalar
CmpH.s_mapWc_in	1.83269764	Corrected mass flow rate scalar
TrbH.NcDes	6698.73912 rpm	Design corrected speed
TrbH.s_mapEff_in	1.02257859	Isentropic efficiency scalar
TrbH.s_mapNc_in	1	Relative corrected speed scalar
TrbH.s_mapPR_in	1.86009916	Pressure ratio scalar
TrbH.s_mapWc_in	1.50370948	Corrected mass flow rate scalar
TrbL.NcDes	2990.36021 rpm	Design corrected speed
TrbL.s_mapEff_in	1.00619495	Isentropic efficiency scalar
TrbL.s_mapNc_in	1	Relative corrected speed scalar
TrbL.s_mapPR_in	1.38658958	Pressure ratio scalar
TrbL.s_mapWc_in	0.163377115	Corrected mass flow rate scalar

Source: the Author.

Chart 5 – Boundary variable to be designed and input data.

Boundary to be Designed Locally	
Boundary	**Description**
FN	Total net thrust
Local Point Input Data	
Data	**Description**
Amb.MNf_in	Input Mach number
Amb.alt_in	Input altitude
Amb.dTs_in	Input delta temperature from selected atmosphere

Source: the Author.

The procedure described increases the complexity of the equation system by adding twenty-nine additional equations or inequalities into the simulation. For the sake of simplicity, it was decided to work only with equations, always only declaring the variables and their values previously used.

The distribution of the equations between the design points, seen in Chart 6 (their values are shown in Table 2), was done mainly by consulting the literature and by focusing on the engine performance in cruise. Indeed, when sizing for several points of the flight, it is desired to optimize the yields of the components during the cruise and to size the maximum capacities of the engine for take-off and the end-of-climb due to its technological and installation limits (temperature and specific flow).

Chart 6 – Separation of variables for engine design.

Point Design	**Variables**
Take-off	BPR, NH, NL, W1, Tt41
End-of-climb	FN, P3Q25, CmpFan.BETA, CmpFan.Beta_sec, CmpFan.NcRdes, CmpFan.NcRdesMap, CmpFan.NcRdesMap_sec, P21Q2, P13Q2, CmpH.BETA, CmpH.NcRdes, CmpH.NcRdesMap, TrbH.NcRdes, TrbH.NcRdesMap, TrbH.ZETA, TrbL.NcRdes, TrbL.NcRdesMap
Cruise	FN, EP21, EP13, EP3, EP43, EP5

Source: the Author.

The most important advantage of this procedure in comparison with the previous method is that it gives both the main and secondary axis rotation speeds for maximum Climb and maximum Cruise conditions, no longer being necessary to make an estimate for these flight regimes, i.e., no longer being necessary to consider a value of 98% and 96% of the nominal speed at take-off, respectively. So, whatever the distribution of variables, it is very interesting that engine design can provide the values of the axis rotation speeds to have a more reliable performance calculation.

3.3.2 Including data for fuel flow

To complete the mission analysis, it is necessary to deduce the fuel consumption over the entire mission as function of thrust for each altitude and Mach number (OATES, 1989). Indeed, the fuel flow is a major factor in the aircraft range, being then one of the most important parameters for design (SEITZ, 2011). Despite the performance charts obtained for MTO, MCL and MCR having the fuel flow, the aircraft does not fly all the time in maximum performance conditions, mainly during cruise due to flight restrictions. Therefore, not having simulated fuel consumption might have prejudiced the coupling.

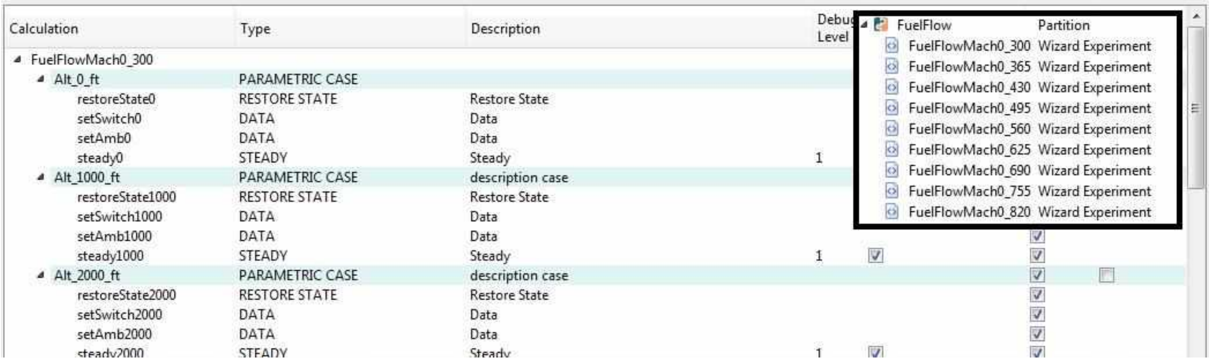
To structure the simulation of fuel consumption in possible cruise flight scenarios, it was decided to consider the thrusts at maximum cruise as reference. In fact, at this working condition, there is no limit of the engine operating time (MARTIN, 2009). Therefore, during almost the entire flight the engine operates at these maximum thrusts or, most likely, at a lower thrust.

To build this “thrust possibility field”, it was decided to make simulations where it was calculated the fuel consumption for various thrusts by considering the same flight condition, i.e., the same flight Mach number and altitude. Thus, it was taken an interval of 40% to 100% of the maximum thrust provided for the maximum cruise data, with a step of 10%.

The translation of this methodology on PROOSIS is a bit complicated. Parametric calculations are required for the Mach number, for the altitude and for the thrust, the latter with the complication that, since it must come out of the MCR table, it is too difficult to establish a law of discretization that can link the thrust variation to other parameters. The most logical and simple application found was to separate the simulations by Mach number and to have a single parametric calculation for each altitude: the variation in thrust from 40% to 100% of the maximum value. The structure of these simulations is found in Figure 14.

As discussed in section 3.2.4, enough information about fuel consumption at idle condition was not found in the literature, so it was not possible to obtain a performance data for this engine working operation used in the flight envelope after cruise.

Figure 14 - Parametric simulations for fuel consumption at Mach 0.300.



Calculation	Type	Description	Debug Level			
FuelFlowMach0_300						
Alt_0_ft	PARAMETRIC CASE					
restoreState0	RESTORE STATE	Restore State				
setSwitch0	DATA	Data				
setAmb0	DATA	Data				
steady0	STEADY	Steady	1			
Alt_1000_ft	PARAMETRIC CASE	description case				
restoreState1000	RESTORE STATE	Restore State				
setSwitch1000	DATA	Data				
setAmb1000	DATA	Data			☑	
steady1000	STEADY	Steady	1	☑	☑	
Alt_2000_ft	PARAMETRIC CASE	description case			☑	☐
restoreState2000	RESTORE STATE	Restore State			☑	
setSwitch2000	DATA	Data			☑	
setAmb2000	DATA	Data			☑	
steady2000	STEADY	Steady	1	☑	☑	

FuelFlow	Partition
FuelFlowMach0_300	Wizard Experiment
FuelFlowMach0_365	Wizard Experiment
FuelFlowMach0_430	Wizard Experiment
FuelFlowMach0_495	Wizard Experiment
FuelFlowMach0_560	Wizard Experiment
FuelFlowMach0_625	Wizard Experiment
FuelFlowMach0_690	Wizard Experiment
FuelFlowMach0_755	Wizard Experiment
FuelFlowMach0_820	Wizard Experiment

Source: the Author.

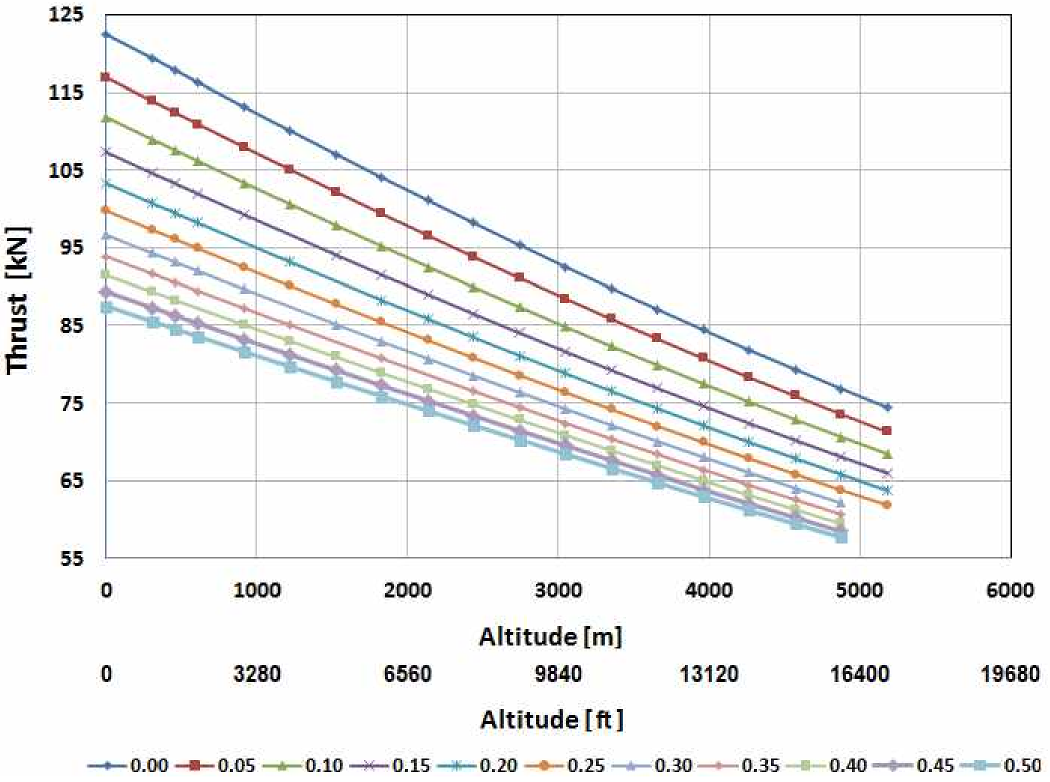
4 RESULTS AND DISCUSSIONS

4.1 Data for maximum engine performance

With the new sized engine, calculations have been launched to obtain the maximum engine performance for take-off, climb and cruise. These calculations were done with a different discretization for altitude, Mach number and ISA temperature deviation to improve the data and optimize the simulation. It was adopted a step of 1000 ft for the altitude and included the altitude of 1500 ft just for MTO. The flight Mach number step increased from 0.041 to 0.05 for MTO and to 0.065 for the rest, to have a regular step between 0.3 and 0.82 and at the same time to maintain a step between 0.05 and 0.10, as indicated by Oates (1989). Moreover, it was removed simulation points for MCR and MCL where the Mach number is less than 0.3.

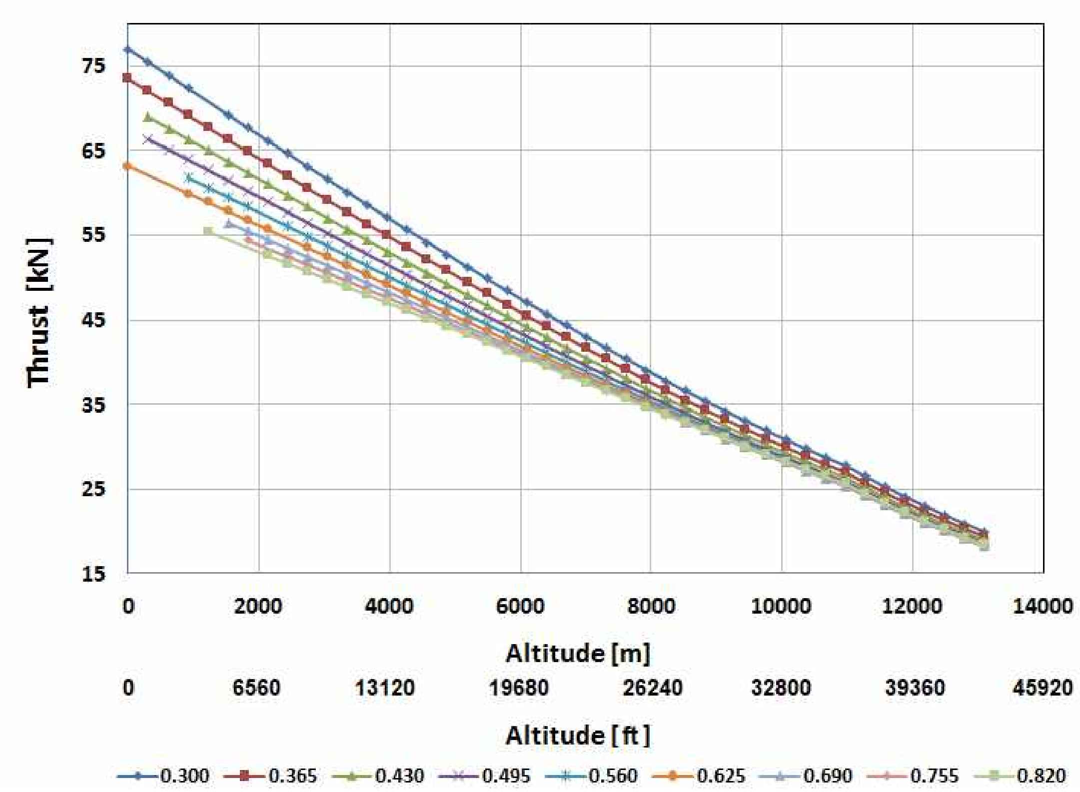
The results can be seen in Graphics 7, 8 and 9. It can be noticed that the sizing done considering maximum take-off, end-of-climb and cruise allowed obtaining performance data, even above 10 000 m, which was not possible before.

Graphic 7 - MTO engine thrust at ISA +0 K by PROOSIS.



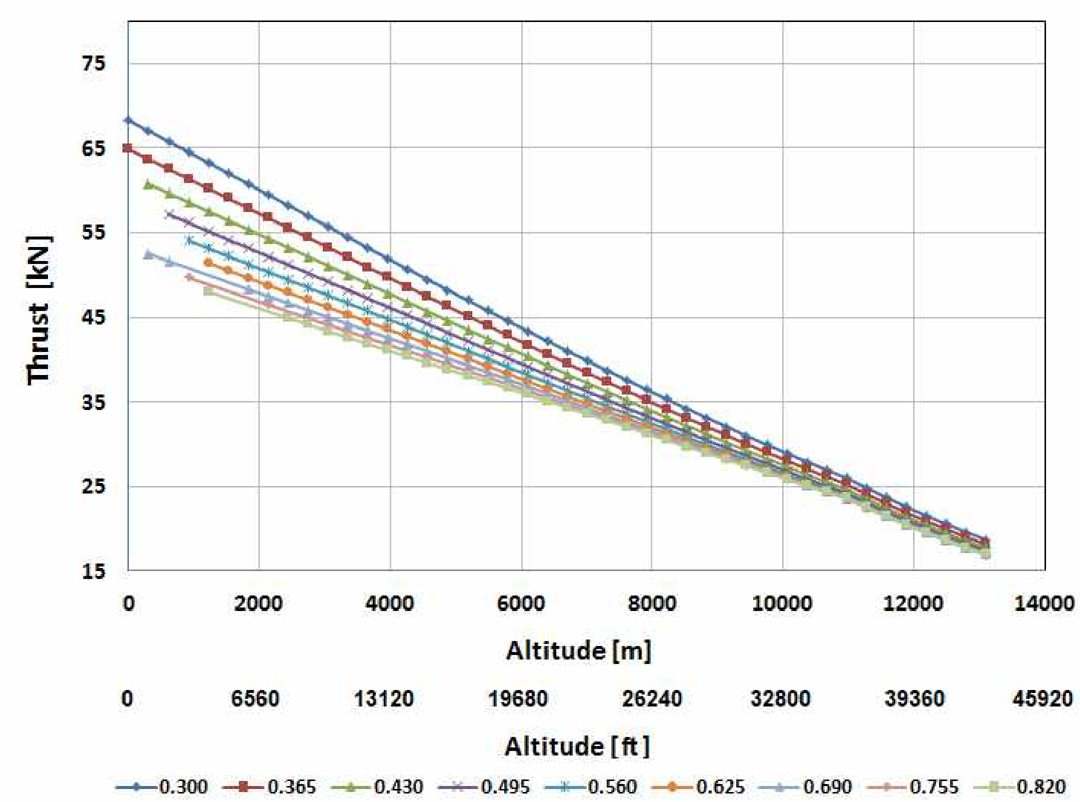
Source: the Author.

Graphic 8 - MCL engine thrust at ISA +0 K by PROOSIS.



Source: the Author.

Graphic 9 - MCR engine thrust at ISA +0 K by PROOSIS.



Source: the Author.

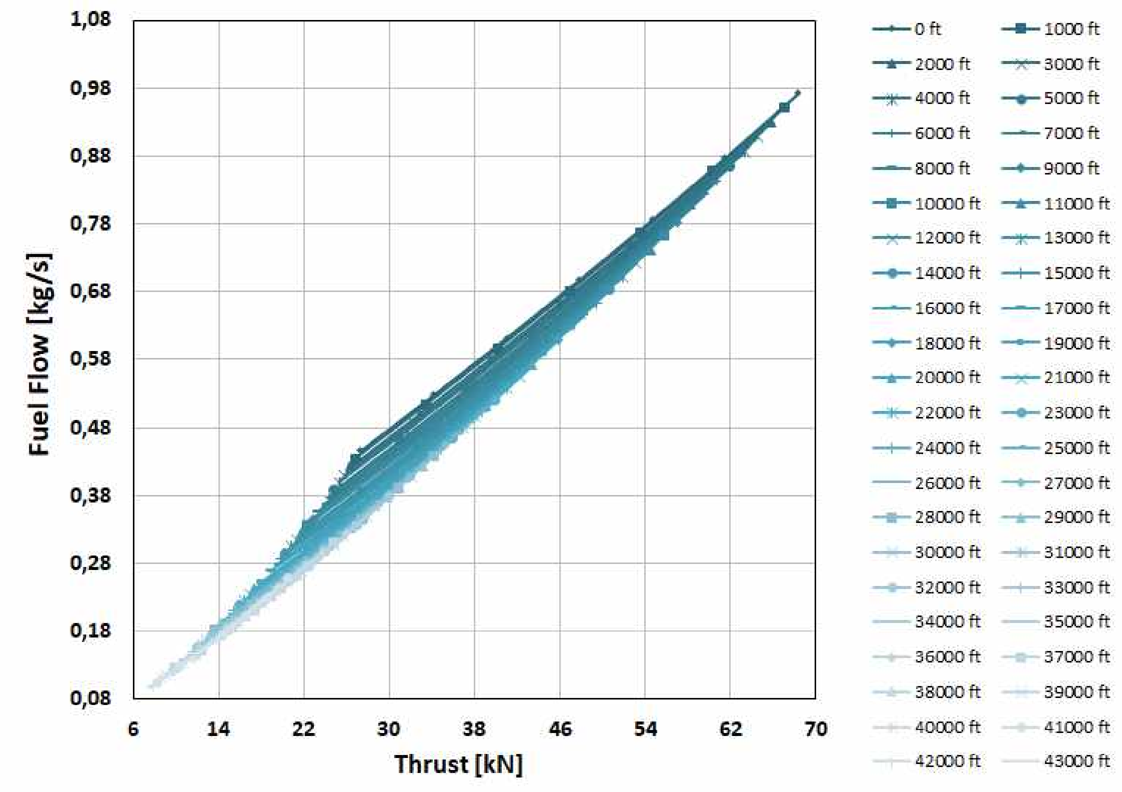
There are problems for higher Mach numbers at low altitude, however this does not affect coupling due to the speed limits which mainly exist below 10000 ft and is considered by the aircraft simulation. For sure, unless otherwise authorized by the regulatory agencies, no pilot may operate an aircraft below 10 000 feet at an indicated airspeed of more than 250 knots (GUDMUNDSSON, 2014), which corresponds to a Mach limit of 0.39.

4.2 Data for fuel flow

The results can be seen in Graphics 10, 11, 12, 13, 14, 15, 16, 17 and 18. They were produced after processing the data to eliminate those with a problem in the simulation, what is indicated by the software itself.

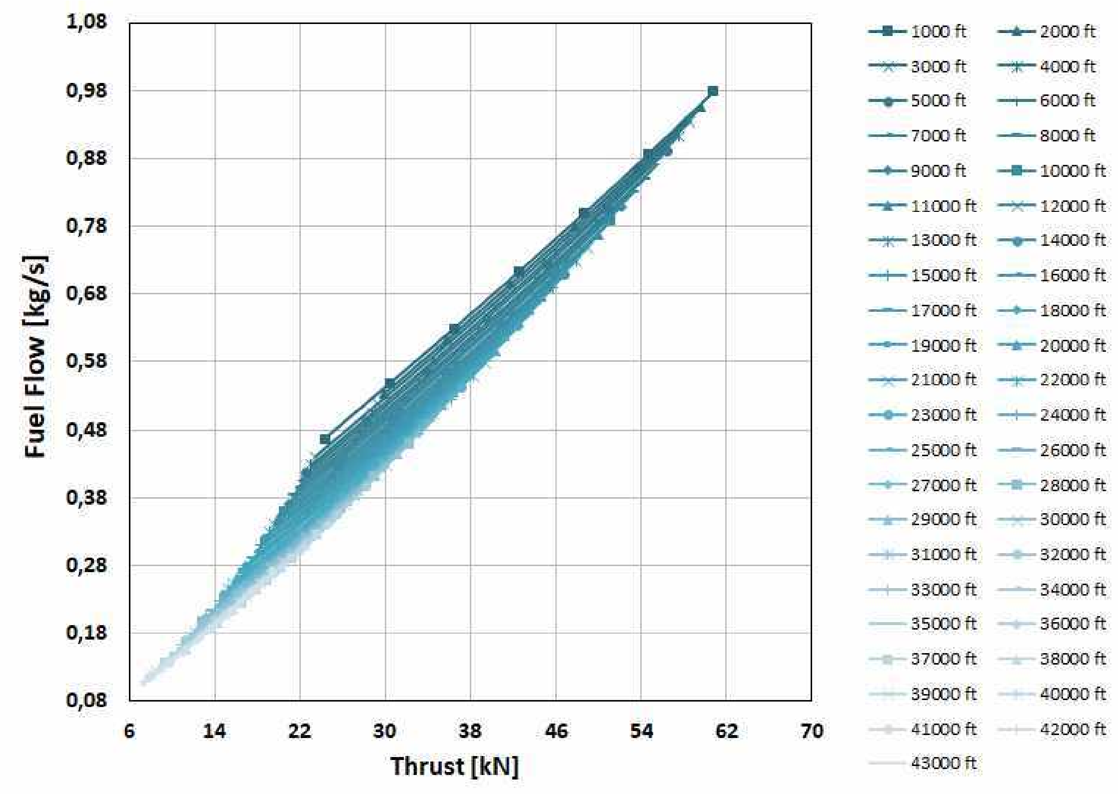
In fact, as it was occurred for the maximum engine performance, the built model presents difficulties for the simulation of high speeds at low altitudes. Despite indicating a possible modelling or dimensioning problem, such data would not be necessary also due to speed restrictions.

Graphic 10 - Fuel Flow simulated at Mach 0.300.



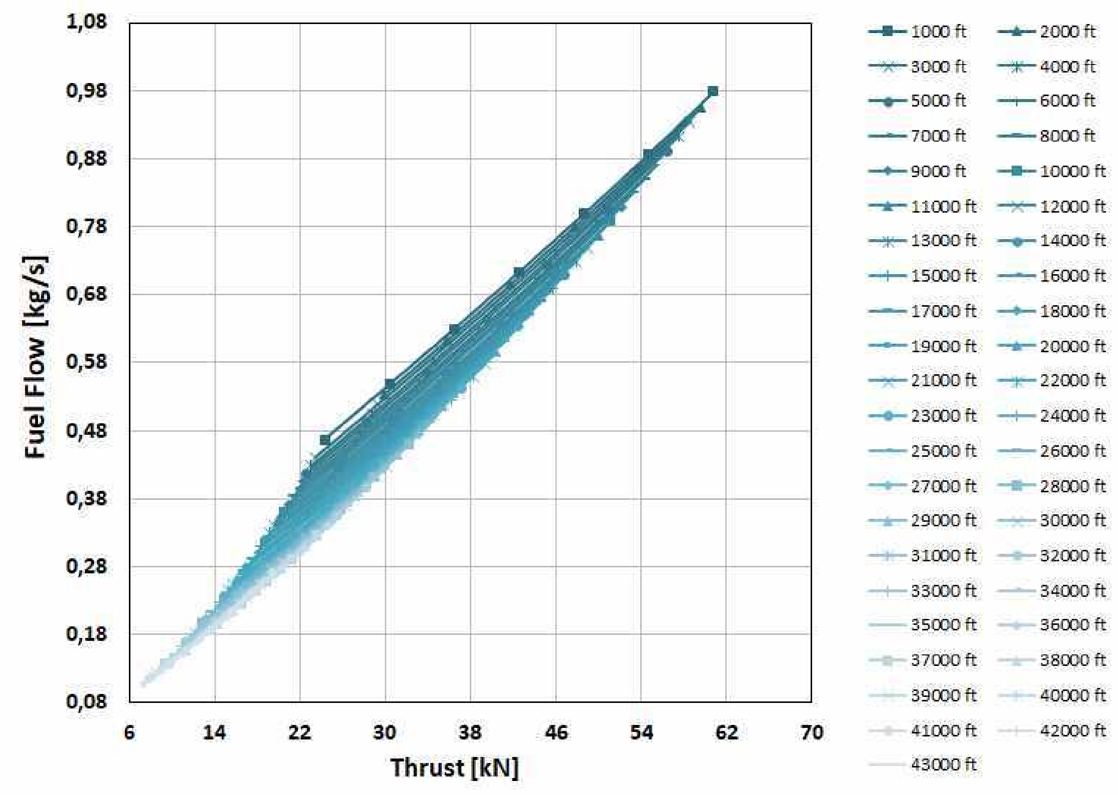
Source: the Author.

Graphic 11 - Fuel Flow simulated at Mach 0.365.



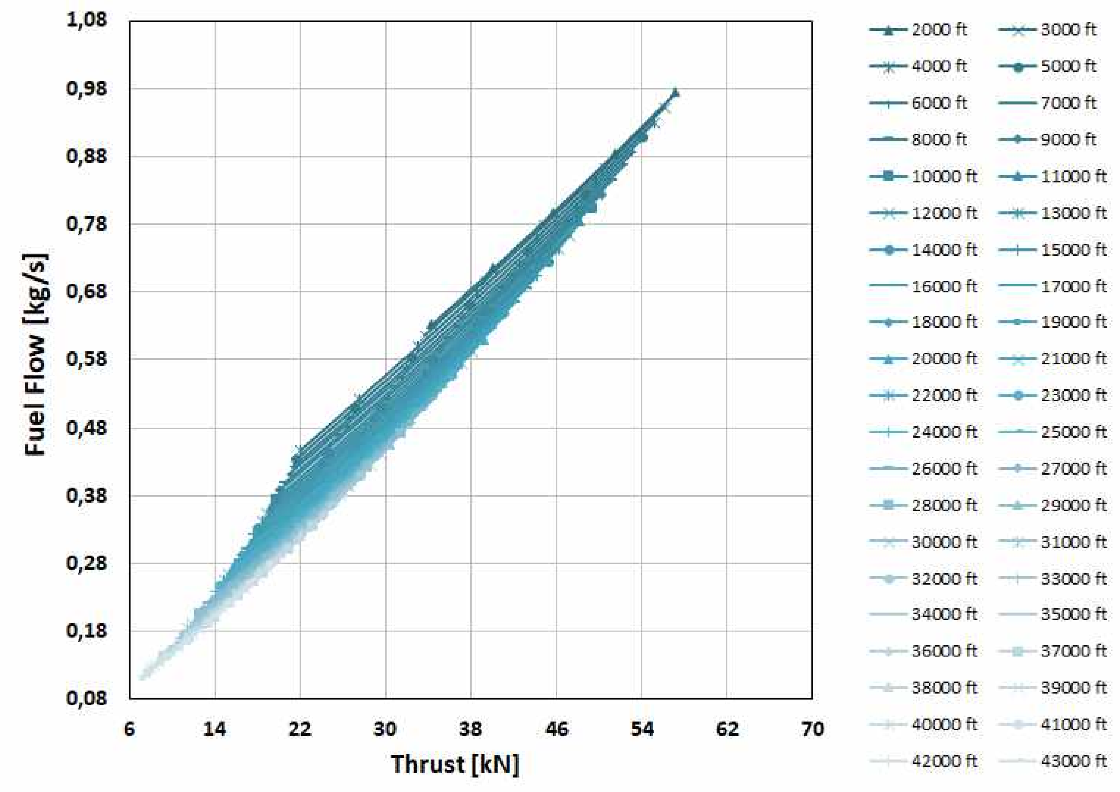
Source: the Author.

Graphic 12- Fuel Flow simulated at Mach 0.430.



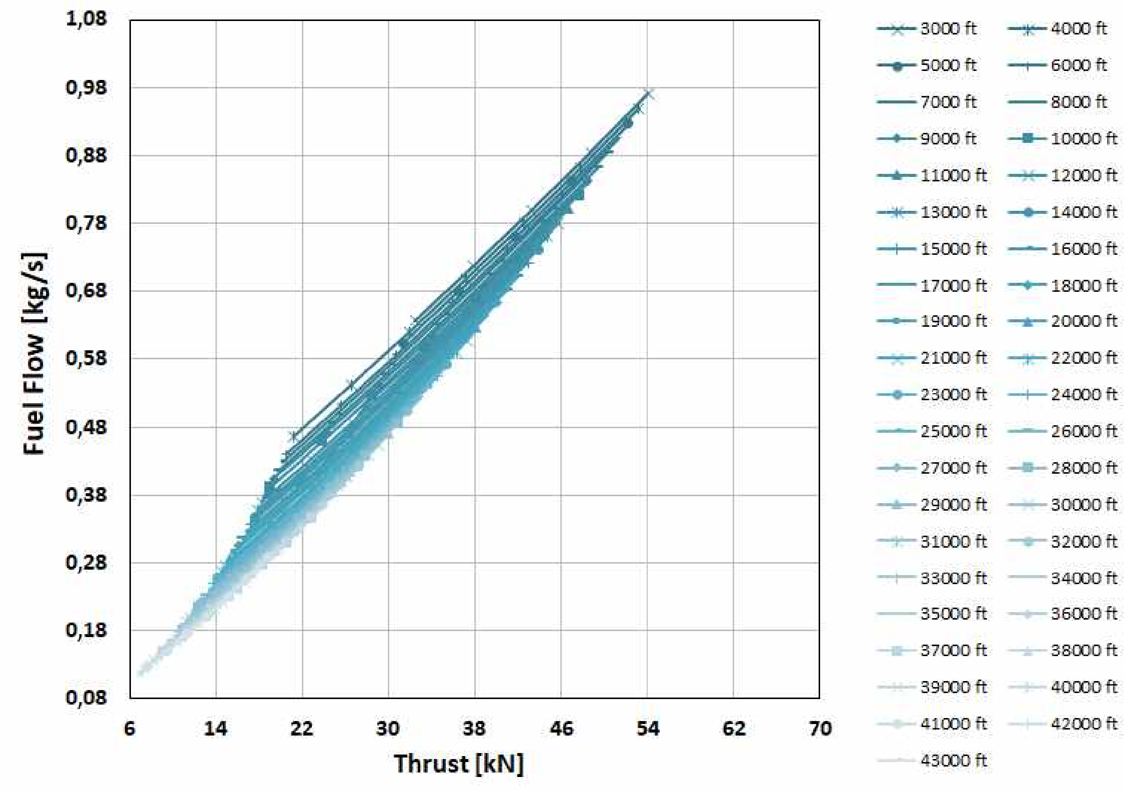
Source: the Author.

Graphic 13 - Fuel Flow simulated at Mach 0.495.



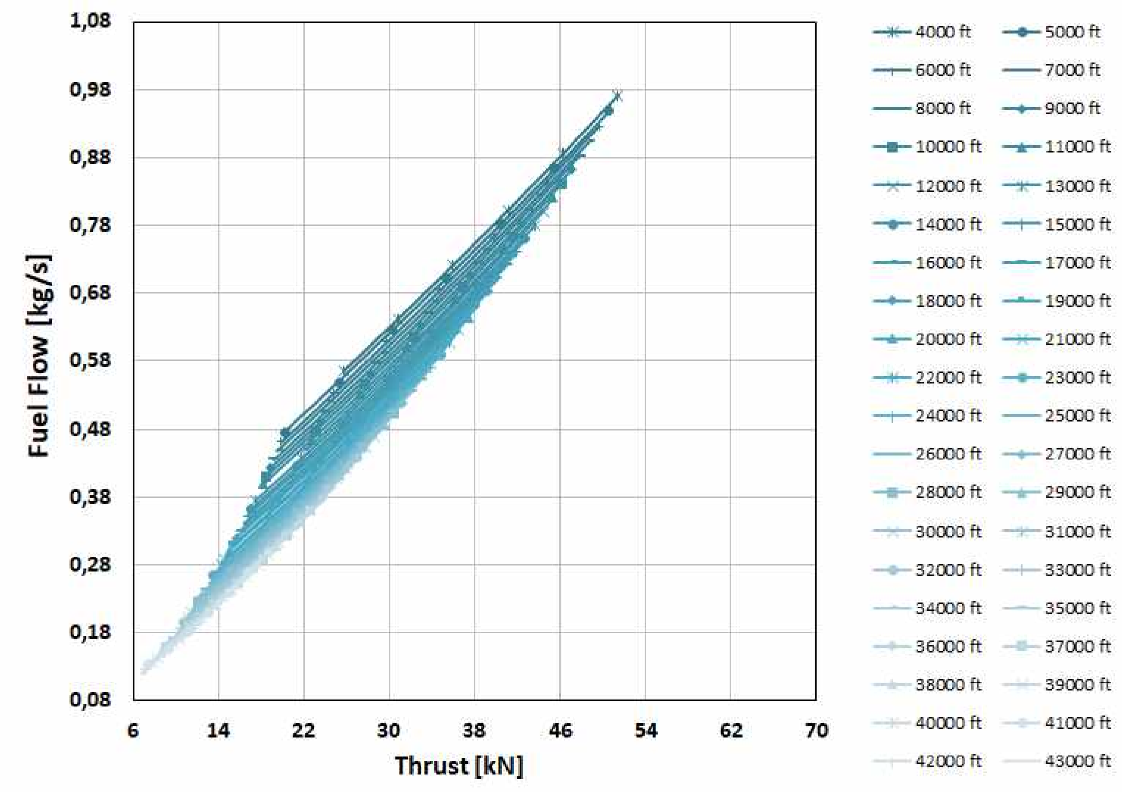
Source: the Author.

Graphic 14 - Fuel Flow simulated at Mach 0.560.



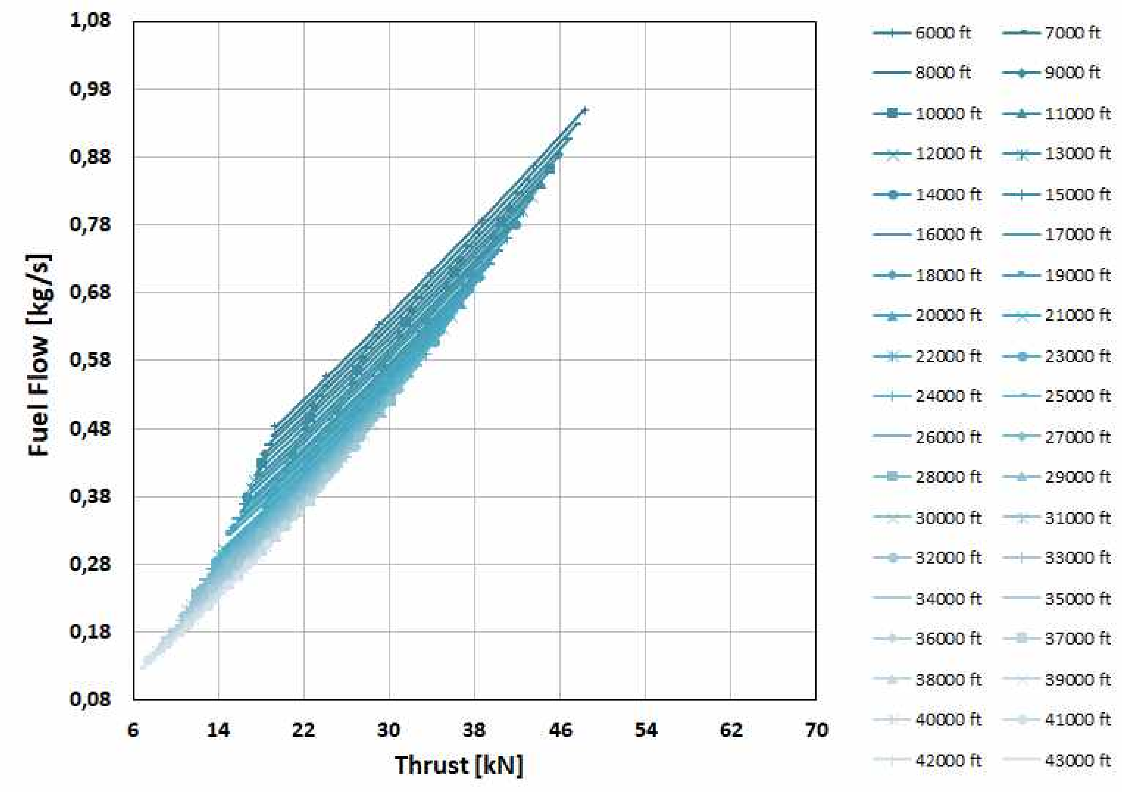
Source: the Author.

Graphic 15 - Fuel Flow simulated at Mach 0.625.



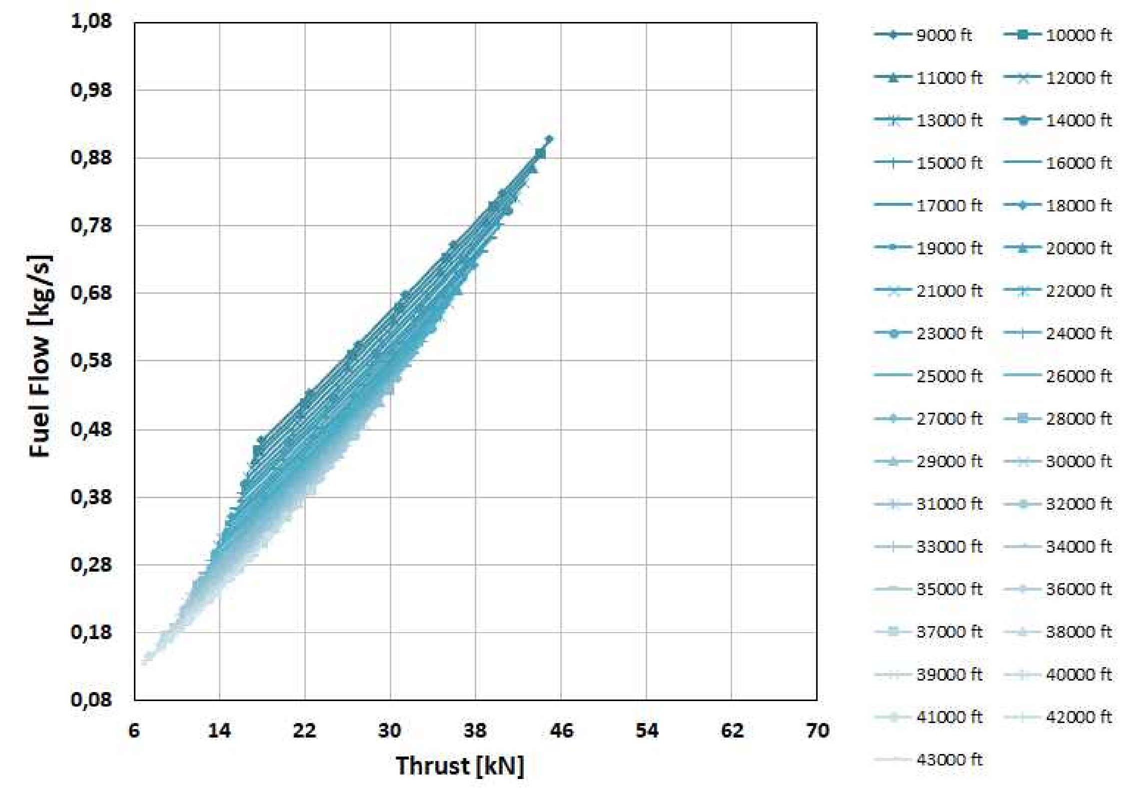
Source: the Author.

Graphic 16 - Fuel Flow simulated at Mach 0.690.



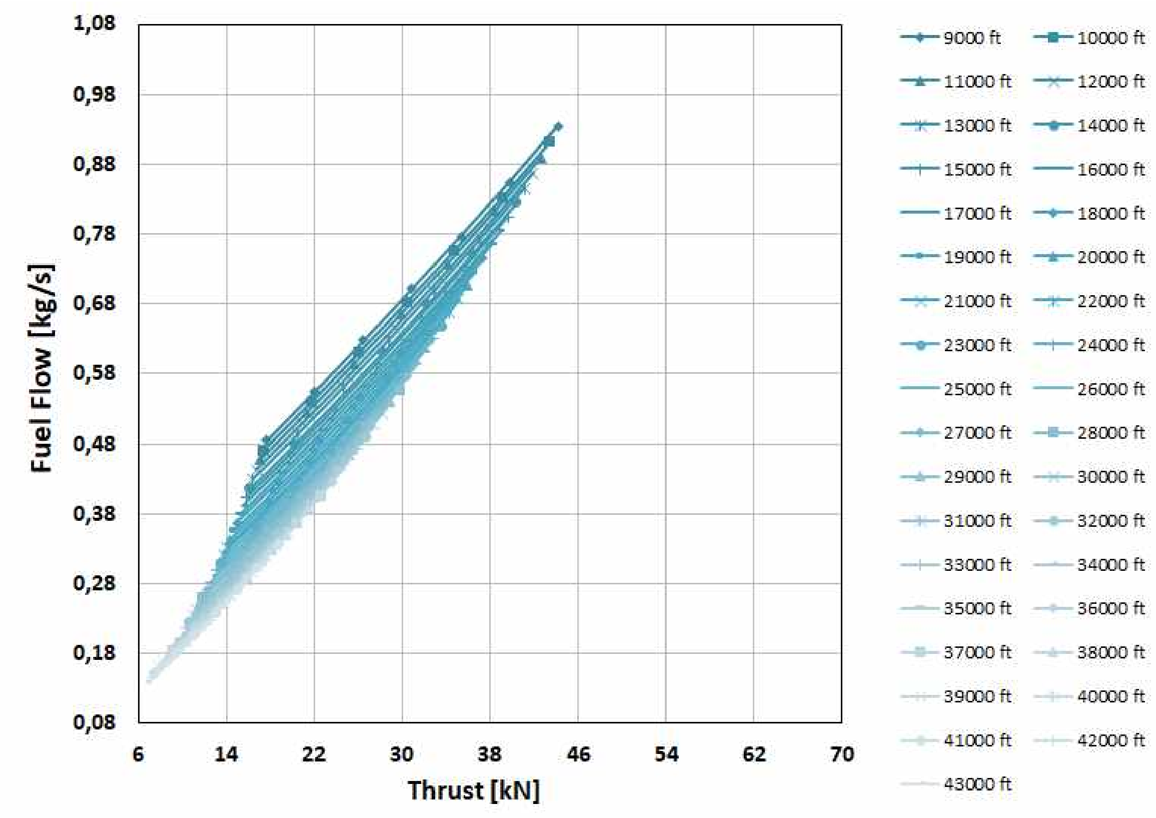
Source: the Author.

Graphic 17 - Fuel Flow simulated at Mach 0.755.



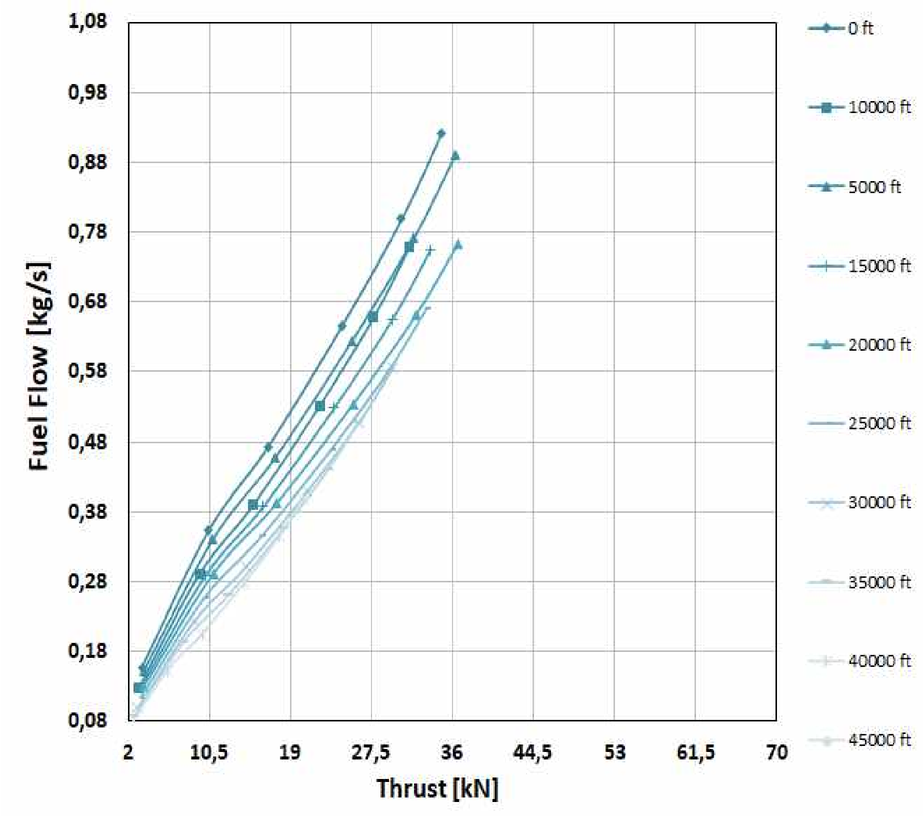
Source: the Author.

Graphic 18 - Fuel Flow simulated at Mach 0.820.



Source: the Author.

Graphic 19 - Fuel Flow of Pacelab APD engine model at Mach 0.820.



Source: the Author.

Looking at the fuel flow graph for Mach 0.82 given by Pacelab APD for the default-small engine model, Graphic 19, it is evident the difference between this model and the data obtained by PROOSIS. However, despite the coupling model having a more consistent behaviour, since there is no reference in the literature for a direct comparison, it is not clear which graph is more representative of the true fuel flow of the CFM56-7B engine.

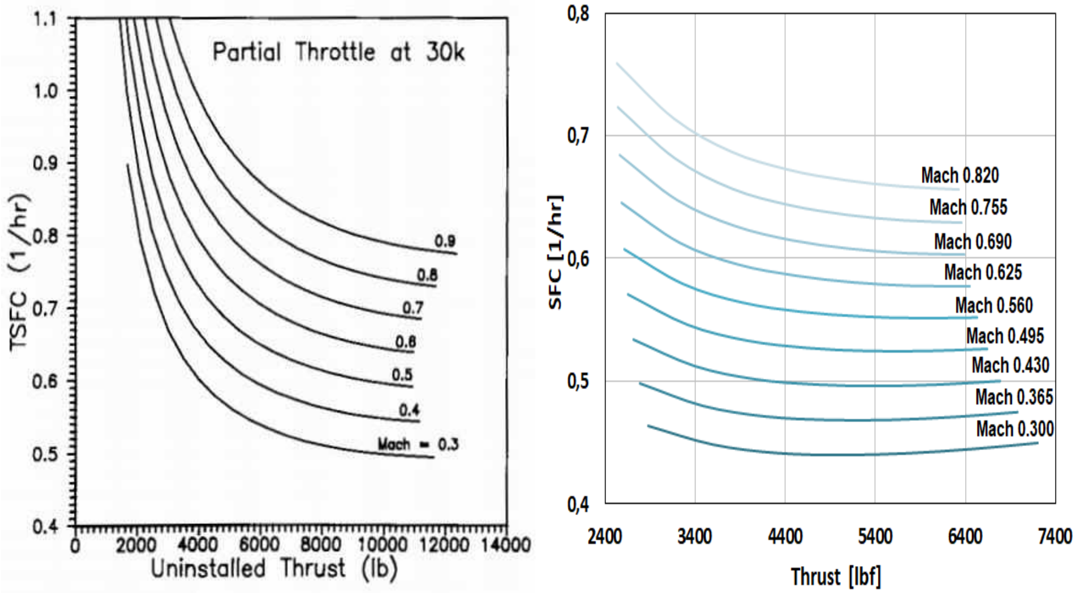
Nevertheless, Torenbeek (1982) and Raymer (2006) provide some Specific Fuel Consumption (SFC) curves for generic models of turbofan engines. SFC is one of the most important metrics for an engine because it “indicates how efficiently a power plant converts chemical into mechanical energy” (GUDMUNDSSON, 2014). It is defined as a ratio between the fuel flow and the thrust (see Equation 13).

For an engine with 50000 lb_f as nominal thrust and a bypass ratio of 8.0, Raymer (2006) gives the following curves for SFC at 30000 ft shown in Figure 15. Even with different characteristics, a certain comparison can be made with the engine modelled and simulated in PROOSIS, since the differences would be mainly in the absolute values and not in the trends of the curves (it is practically the same architecture and the same principle of operation). Thus, analysing the curves for the SFC of the

PROOSIS model for practically the same flight conditions, a certain similarity between the two graphs can be observed. It is necessary to emphasize that simulations were not carried out for low thrusts (the range was between 40% and 100% of the maximum thrust at cruise condition). This similarity between the graphs has been identified for all altitudes.

For a correct and definitive validation of the data found, a comparison with the performance tables provided by the engine manufacturer from its own simulations and certification tests was needed. However, such information has access restrictions due to patent protection and technological power involved in the project.

Figure 15 – Left: SFC for a high bypass turbofan engine at 30000 ft. Right: SFC for the PROOSIS engine model at 30000 ft.



Source: Raymer (2006) and the Author (right).

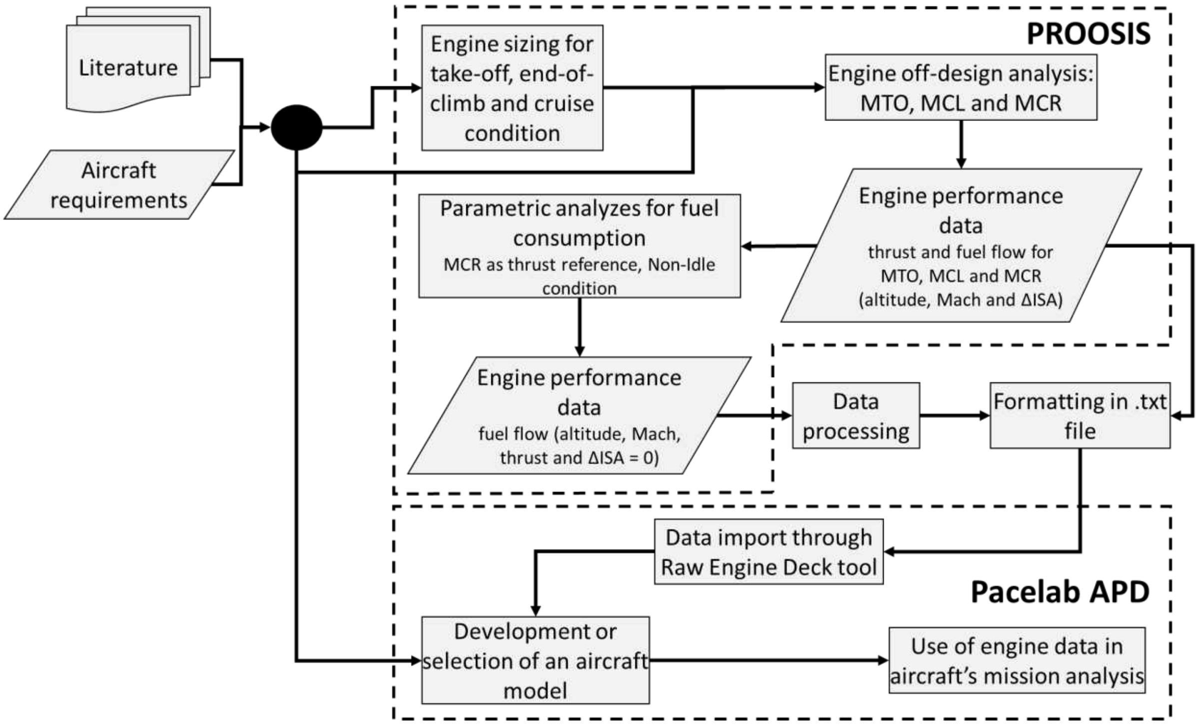
4.3 Coupling routine: state-of-the-art

The current coupling process is described in Figure 16. Based on data and models already existing in the literature, the engine is designed on PROOSIS and sized for the most critical working conditions. At the end of the design phase, the resulting rotational speeds values for the critical operation points are taken and used in the off-design simulation. Therefore, the data for the maximum engine performance is obtained.

To obtain more data of fuel consumption, new simulations are carried out through parametric analyses having the thrust at maximum cruise as reference.

Afterwards, the data obtained are processed to eliminate the values that have not been well converged, i.e., the points that present abnormal values for fuel consumption or thrust in comparison to the others in the same engine operating condition. Finally, the data is organized according to its rating code (RC) and formatted in a .txt file: RC 50 for MTO, RC 40 for MCL, RC 35 for MCR and RC 0 for Fuel Flow Non-Idle. The template of the .txt file can be found in Figure 17.

Figure 16 - Current Coupling Procedure.



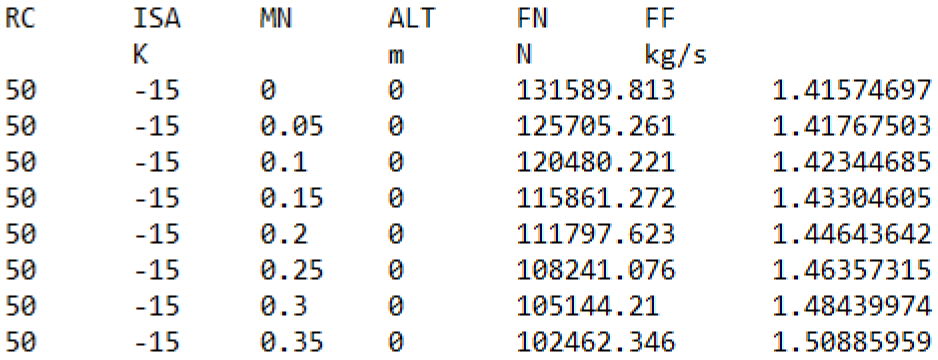
Source: the Author.

To finish the coupling, the Raw Engine Deck tool of the Pacelab APD Engineering Workbench is used because it reads the .txt file and processes the data from the RC and acronyms. Once the import is complete, the new engine model can be saved on Pacelab APD and used several times.

Using this routine, the engine modelled on PROOSIS resulted in a gain of 209 nm in the aircraft range, which achieved 98% of the real range of the Boeing 737-800. For purposes of comparison, with the engine model used previously by Pacelab APD, the aircraft design achieved 91% of the real range indicated by the manufacturer.

This coupling procedure presents some problems and weaknesses. Indeed, the engine performance and fuel consumption for Idle condition are still missing, so the model must use the data already available on Pacelab APD. To improve data quality for all flight regimes, it must be found a way to define this operating condition on PROOSIS to carry out the necessary simulations.

Figure 17 - Example of a .txt file type used in the coupling.



```
RC      ISA     MN      ALT     FN      FF
        K               m       N       kg/s
50      -15     0       0       131589.813      1.41574697
50      -15     0.05    0       125705.261      1.41767503
50      -15     0.1     0       120480.221      1.42344685
50      -15     0.15    0       115861.272      1.43304605
50      -15     0.2     0       111797.623      1.44643642
50      -15     0.25    0       108241.076      1.46357315
50      -15     0.3     0       105144.21       1.48439974
50      -15     0.35    0       102462.346      1.50885959
```

Source: the Author.

Structuring the simulations to obtain more fuel consumption data requires a lot of manual work due to the necessary number of Experiment and Parametric Cases, as can be seen in Figure 14.

Moreover, the data processing is not automatic, it is necessary to perform the desired procedures manually with available software such as Microsoft Excel or MATLAB. It would be interesting to establish elimination criteria based on statistical indicators and to do this processing in an automatic manner.

4.4 Ways to improve the coupling routine

With the consolidation of the manual incorporation of performance data, more advanced coupling possibilities can be discussed. Currently, these possibilities are based on the ability of PROOSIS to enable the use of its simulations in other formats and software, and the open architecture feature of Pacelab APD.

Indeed, the closure of the coupling routine in a loop must be pretended, once the current method is completely unidirectional: from PROOSIS to Pacelab APD, and, as discussed in the Chapter II, this do not reproduce the real procedure that occurs in the aircraft design. Therefore, the ideal scenario would be to directly use data from Pacelab APD to design the engine on PROOSIS and then to carry out the off-design simulations through a communication platform. However, the parameters used by PROOSIS to size the engine are beyond those used by Pacelab APD. It would be necessary then to add more variables to the Pacelab engine object and to link them with the other systems and objects of the aircraft model. Due to the complexity of such coupling, other possibilities for improving the current routine can be made. They are discussed in the following sections.

4.4.1 Improvements in simulation

Still using the performance data import, simulations for maximum continuous and idle rating thrust can be implemented. Although, as stated above, there are no clear definitions in the literature of such conditions in the operating limits of engine components, some clues have been found. For Idle, a possible approach is to define the operating conditions of the engine so that it is still able to power the other systems of the aircraft. Nevertheless, such approach translates more the aircraft requirements than the critical engine working conditions.

According to Martin (2009), the Idle condition is better understood by minimum limits on LP spool speed and HP compressor delivery pressure or fuel. Indeed, Federal Aviation Administration (2006) indicates in CFM56-7B certification the minimum idle in flight as function of range of LP rotational speed and atmosphere temperature.

The possibility of incorporating more elements of interaction between the systems is also observed. In addition to performance data and specific engine operating parameters, other simulations important for the design of the aircraft and the engine can also be implemented, such as the aerodynamic interaction that takes place between the engine and the wing, which directly impacts the drag force of the aircraft, the extraction of compressed air from the engine, the noise generation from engine components and exhaust jet and etc. However, modifications to the Pacelab APD code and PROOSIS components (or even the creation of new components) would be necessary. In addition, another import tool would have to be implemented, since the current one provided by Pacelab APD only imports basic performance data, such as thrust and fuel consumption.

4.4.2 Improvements in processing

In the current routine coupling, problems of simulation convergence and generation of non-representative data are observed. These troubles may come from mainly three reasons (1) bad definition of numerical parameters within simulation, (2) insufficient engine sizing, and (3) simulation of flight conditions that are physically impossible for the engine.

Since this coupling is intended for a user who has enough technical knowledge in sizing and simulating an engine, points (1) and (2) would probably not occur in a real case. On the other hand, the third reason may still occur, since the current routine must establish simulations for a large variety of flight conditions, mainly for parametric analysis of fuel consumption.

Thus, establishing a processing in the data to eliminate non-representative ones based on statistical indicators can improve the coupling. Furthermore, doing it automatically would be indispensable since thousands of data are generated during the simulation.

There is several software that can analyse and manipulate the data. However, their use would only be indicated for a highly manual coupling routine, as adding one more system to a more automatic coupling would increase its complexity and, consequently, its unpredictability.

The ideal scenario would be to incorporate this processing into the PROOSIS or even into Pacelab APD. However, doing it in PROOSIS could be more advantageous, due to the possibility of having more access to information about each simulation, e.g., convergence criteria and residual analysis. Thus, a more judicious and reliable procedure could be implemented.

4.4.3 Coupling automation

As described by Bala et al. (2007), an advantage found in PROOSIS the flexibility in the visualization of the simulation results. Indeed, PROOSIS can generate decks that can be used by other users for off-design performance studies to evaluate the engine behaviour for a flight envelope (ALEXIOU; TSALAVOUTAS, 2011).

Therefore, the use of a Deck generated by PROOSIS can replace the slow procedure for obtaining data for fuel consumption and thrust at maximum working conditions. Thus, instead of using the Multidimensional Data Tables to obtain engine performance throughout the flight, Pacelab APD could use the deck, which would contain the engine sized, to obtain the performance data necessary to aircraft's mission calculation. However, to code this solution the incompatibility of the programming language between the software would be a problem to be solved.

Following the same reasoning, the simulation codes automatically generated by PROOSIS, which can be organized in a .dll library or in a small software, could be used by Pacelab APD. Thus, a more generic engine model could be encapsulated in codes, allowing not only off-design analyses but also the engine sizing itself. Nevertheless, the problem of incompatibility of language would be remaining. Moreover, in addition to having a restricted model, the level of work required to establish this coupling could approach that needed to create a definitive communication module between the software.

4.5. The routine generalization capacity

The coupling was established based on the issues of a gas turbine engine, more specifically a turbofan. Thus, some choices made during the engine sizing and off-design analysis process may, theoretically, only concern this type of propulsion system.

Therefore, some considerations about the generalization of the routine achieved must be made, mainly considering the market trend for a more electric aircraft:

Engine and aircraft sizing - in other types of engines and aircrafts, other parameters and requirements may be more important. For a military application, elements such as the engine size, the ability to operate in critical regimes for a long time, or even the use of an afterburner can impact the design more than only thrust, fuel consumption and noise requirements (LASKARIDIS, 2000). Fore a more electric aircraft, the relationship between the thrust provided by the engine and the need for batteries and, consequently their weights, is so critical that it becomes one of the most determining factors in the design of the aircraft (PORNET et al., 2014). Thus, the requirements at the beginning of the routine should be adapted according to the peculiarities of each application. Pornet et al. (2014) and Laskaridis (2000) provide a lot of information for the requirements definition for both cases.

Off-design analysis - the factors that relate the maximum operating conditions of the propulsion system to its physical limits may also vary according to the type of engine. However, even in hybrid energy engines, the rotational speed limits of the shaft are decisive (PORNET et al., 2014). According to the authors, what can also be important in these cases is the maximum amount of power that can be extracted from each part of the propulsion system, electrical and combustion engine, according to the segment of the flight. Thus, minor impact adaptations may be required for the coupling.

Fuel consumption - there is no sense in discussing fuel consumption in fully electric propulsive systems, while for a military aircraft, fuel consumption is much more complex and dependent on the type of design mission and engine architecture. Thus, this part of the routine is very likely to be profoundly modified if it is not used for a general aviation application. However, except for a completely electric motor, the essence of the simulation would be the same: parametric analysis with thrust and flight conditions as parameters.

5 CONCLUSION

In this study, a first step was made towards coupling routine developed between two simulation software used in the aircraft design, PROOSIS and Pacelab APD. To guide it, a critical judgment of the interactions that exist between some aircraft systems was indispensable, mainly between the airframe and the engine.

Therefore, from the performance data obtained through PROOSIS, a classical turbofan engine model, built and simulated in this tool, was incorporated into Pacelab APD, using a real engine as an example. This model caused changes in the mission analysis of an aircraft, which design is provided by the tool, resulting in decreased fuel consumption and increased aircraft range.

For this, it was necessary to determine the variables required for the coupling implementation, prioritizing the design issues of the propulsion system, as well as for the simulation of its different working conditions, such as take-off, climb and cruise.

This first approach allowed the discussion about other coupling possibilities between the tools, as well as about some improvements in the achieved routine to increase its robustness and accuracy.

Thus, despite the absence of a real validation of the engine model made for the coupling, the established routine gave significant improvements in the aircraft mission analysis, due to changes in the parameters and performance indicators of the aircraft. The achieved 7,5% gain in the range showed the impact that can be in the design of an aircraft with the use of more accurate models even in the initial stages of the project. Indeed, as defended by Torenbeek (1982), the best engine for a given aircraft can only be developed through a long and close collaboration between aircraft and engine manufactures, allowing an effective exchange of information and data.

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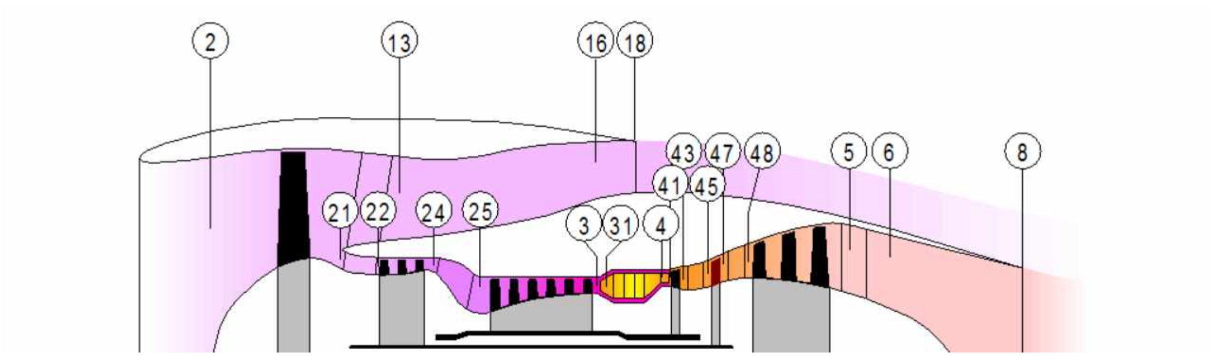
ANNEX A - TURBOFAN PLAN IDENTIFICATION



Source: GASTURB (2020).