POLITECNICO DI TORINO

Corso di Laurea Magistrale in Ingegneria Aerospaziale

TESI DI LAUREA MAGISTRALE

Analysis of Cost drivers impact on Direct Operating Costs estimation of a hypersonic point-to-point vehicle

Relatore:
Prof. Nicole Viola

Candidato:
Margherita Pincini

Correlatori:
Ing. Davide Ferretto
Ing. Roberta Fusaro
Ing. Valeria Vercella

Marzo 2018

Abstract

The objective of the thesis is the evaluation of the Direct Operating Costs (DOCs) of a hypersonic point-to-point vehicle for the civil transportation, considering the impact of the new technologies on the cost items. This is possible using a mathematical model developed by the NASA in 1972. The Cost Evaluation Relationships (CERs) are based on the features of the vehicle. The reference vehicle for the estimation is the LAPCAT A2, designed by the European Space Agency.

From this thesis, it is underlined the importance of correct evaluation of the direct operating costs just from the first phases of project. This is not easy in the case of hypersonic aircraft, because few information is available and the comparison with the subsonic jet is not always accurate. It is necessary a mathematical model that can be applied when few data about the performances and physical features are defined. The CERs should also give the possibility to evaluate the impact of new technologies of the aircraft on the direct operating costs.

After an examination about the Life Cycle Costs (LCCs) of aircrafts, the Direct Operating Costs (DOCs) are described and some mathematical models for the evaluation are presented.

Subsequently, the most interesting hypersonic projects are introduced and the LAPCAT A2 features and performances are detailed.

Then, it is presented the NASA methodology for the evaluation of the Direct Operating Costs of hypersonic vehicle. A careful analysis shows how the most relevant equations under a technological point of view are the one for evaluating the DOC of the fuel and of maintenance. The configuration of the vehicle and the propulsive systems are the hypersonic technologies that have more impact on the Direct Operating Costs. For this reason, the NASA equations have been rewritten exploiting the Breguet formulation of the range. It is an aeronautical relationship that depends on the aerodynamic and the propulsive features of the vehicle.

After that, it is developed a MATLAB tool for the evaluation of the Direct Operating Costs of hypersonic point-to-point vehicle based on the NASA CERs. The presence of Graphic User Interfaces (GUIs) makes the cost estimation straightforward even for inexpert users.

At last, in this thesis, the NASA equations are applied to the LAPCAT A2 for the DOCs evaluation. In conclusion, it is shown that the Direct Operating Costs of a hypersonic vehicle are higher than the ones of subsonic aircraft and that the most relevant cost item is the fuel one. For this reason, it is decided to evaluate the direct operating costs for the reference vehicle considering different productive scenarios of liquid hydrogen. At the end, the equations modified with the Breguet formula of range are used for the evaluation of the DOC of fuel and maintenance. The values obtained are compared with the ones of the NASA equations, to validate them and the modified equations.

Sommario

L'obiettivo di questa tesi è la valutazione dei costi diretti operativi di un velivolo ipersonico punto-punto per il trasporto passeggeri. Importante è l'analisi dell'impatto delle nuove tecnologie su questi costi. Questo è possibile utilizzando un modello matematico sviluppato dalla NASA nel 1972. Esso è costituito da una serie di equazioni basate sulle caratteristiche tecniche del velivolo. L'aeromobile di riferimento utilizzato per la stima costi è il LAPCAT A2, progettato dall'Agenzia Spaziale Europea.

Questa tesi vuole sottolineare l'importanza di effettuare una corretta valutazione dei costi operativi già dalle prime fasi di progetto. Questo risulta difficile nel caso di velivoli ipersonici, poiché le informazioni disponibili circa le caratteristiche fisiche e le performance sono scarse e il confronto con velivoli subsonici non è da considerarsi accurato.

Per prima cosa, vengono esaminati i Life Cycle Cost di un velivolo, con particolare attenzione ai costi diretti operativi. Sono, inoltre, presentati alcuni modelli per la stima costi.

Di seguito, si ha una descrizione dei principali progetti in campo ipersonico e tra questi il più significativo risulta essere il LAPCAT A2 del quale vengono riportate le principali caratteristiche.

A questo punto, si ha l'analisi del modello matematico della NASA, il quale è stato utilizzato per il calcolo dei costi diretti operativi. Viene evidenziato come le equazioni più rilevanti da un punto di vista tecnologico siano quelle relative al costo del carburante e della manutenzione, che dipendono fortemente dalla strategia propulsiva e dalla configurazione del velivolo. Per valutare meglio l'impatto di questi driver tecnologici, le equazioni NASA sono state riscritte sfruttando l'equazione di Breguet. Questa è una relazione utilizzata in campo aeronautico per il calcolo del range e dipende dalle caratteristiche propulsive ed aerodinamiche del velivolo.

È stato, inoltre, sviluppato un programma MATLAB basato sulle equazioni NASA per il calcolo dei costi diretti operativi di un velivolo ipersonico punto-punto. Grazie all'utilizzo di interfacce grafiche, la stima costi è resa semplice e chiara anche per utenti inesperti.

In conclusione, vengono riportati i costi diretti operativi del LAPCAT A2, calcolati con la formulazione NASA. Essi sono più alti rispetto a quelli di un velivolo subsonico. Si può vedere come l'elemento più importante sia il costo del carburante. Per questo si è deciso di valutare, i costi diretti operativi al variare del prezzo del combustibile. Infine, vengono anche riportati i costi diretti calcolati utilizzando le equazioni NASA modificate con l'introduzione della formula di Breguet. Questi sono stati confrontati con quelli ottenuti precedentemente al fine di valutarne la correttezza e validare le equazioni NASA modificate.

Acknowledgments

There are some "Thank you " that I must say. One of them goes to my family, another one to my friends and the last one to the supervisors of my Thesis. I prefer to write this part in Italian, because it is easier to me to say what I think and feel.

Il primo e più grande ringraziamento va alla mia famiglia e in particolare ai miei genitori, Cinzia e Renzo. È solo grazie a loro e ai loro sacrifici che ho avuto modo di poter compiere questo percorso. Li ringrazio, soprattutto, per tutto il sostegno che mi hanno dato in questi anni e per avere sopportato me e la mia ansia durante i momenti più complicati. Ovviamente, un grande grazie va anche a mio fratello Luca, che c'è sempre stato, sia quando avevo bisogno di chiacchierare con qualcuno, sia quando mi serviva un passaggio per tornare a casa.

Un altro enorme grazie va alla mia "Famiglia di Torino", a tutte le mie coinquiline di questi anni di università, perché il rapporto che si è creato è qualcosa di veramente profondo e speciale. In particolar modo voglio ringraziare Lucrezia, che mi ha aiutato sia nella vita universitaria che in quella di tutti i giorni fin dal primo moment0 che ci siamo conosciute dandomi preziosi consigli che porterò sempre con me, Ljdia, per avermi regalato il suo sorriso e la sua gioia, e Greta, per aver vissuto con me il rush finale, sopportandomi, consigliandomi e aiutandomi in questi mesi.

Un altro grande ringraziamento va alle mie amiche. Grazie a Marta per questi (quasi) cinque anni passati fianco a fianco sia tra i banchi del Politecnico sia sedute in qualche bar della città. Grazie anche a Maria Laura perché c'è sempre stata, nonostante i chilometri di distanza, e che forse crede a tutto questo più di quanto non ci creda io!

L'ultimo, ma non meno importante, ringraziamento va a chi mi ha seguito in questo lavoro di tesi. Voglio ringraziare la professoressa Nicole Viola per avermi dato l'opportunità di poter lavorare su un aspetto così interessante e innovativo. Ringrazio, inoltre, Roberta Fusaro, Valeria Vercella e Davide Ferretto per avermi aiutato in questo lavoro di tesi e per tutta la loro disponibilità.

Contents

LIST OF FIGURES

LIST OF TABLES

Abbreviations

ASK	Available Seat Kilometers
ATA	Air Transport Association of America
ATR	Air Turbo Ramjet
BEP	Break Even Point
bhr	Block Hour
CAV	Cruise Air Vehicle
CEF	Consumer Price Index
CER	Cost Estimating Relationships
CPI	Consumer Price Index
DMR	Dual Mode Ramjet
DOC	Direct Operating Cost
ESA	European Space Agency
GUI	Graphic User Interface
HST	Hypersonic Cruise Transport
HST	Hypersonic Cruise Transport
IOC	Indirect Operating Cost
ISA	International Standard Atmosphere
LH2	Liquid Hydrogen
NASA	National Aeronautics and Space Administration
QFD	Quality Function Deployment
QFD	Quality Function Deployment
RBCC	Rocket Based Cycle
RBCC	Rocket-Based Combined Cycle
RDTE	Research, Development, Test & Evaluation
ROI	Return of Investment
RPK	Revenue Passenger Kilometers
sfc	Specific Fuel Consumption
SSTO	Single Stage to Orbit
TBCC	Turbine Based Cycle
TBCC	Turbine Based Combined Cycle
TEMS	Thermal Energy Management System
TRL	Technology Readiness Level
TSTO	Two Stage to Orbit
USD	United States Dollars

1. Introduction

In the next years, it seems possible the introduction of hypersonic aircrafts, that can support and replace the traditional subsonic jets for the passengers' transportation. Currently, some international research centers and private companies are studying to design hypersonic aircrafts that gives the possibility to people to reach two antipodal cities in few hours. Those airplanes should be similar to a traditional subsonic jet for their mission, but their technologies are completely innovative. Different configurations and mission profiles are possible. The designers should choose between many various variables.

The design of hypersonic vehicle is a very challenging project that has great costs both for the development and for the production. To financing the project, it is important to have investors both as public institutions and as private enterprises. The stakeholders finance the project, if they have an economic return. This happens if the product is cost-effective. Airline companies decides to buy a new aircraft, if the costs to maintain it operative are not remarkable and they can easily recover the acquisition expenditure of the aircrafts. Those costs are called operating costs and it is important that they are as low as possible to increase the profits of the designers, manufacturers and airline companies.

For this reason, it is important to do a right cost evaluation just from the initial phases of the project. The designer should be able to evaluate all the life cycle costs of the aircraft for understanding if the vehicle can have success on the market. A particular attention should be on the direct operating costs, because if this cost items are low, the number of investors and customers could increase. The profits will be higher and the cost for the production and development will be repaid.

The design engineers are interested to understand the impact of the driver, i.e. the parameters linked directly with the technologies of the aircraft, on the operating cost. This gives them the possibility to evaluate which configuration can be the best under an economic point of view.

For the designers, it is important to have the right cost evaluation just from the begging phase of the project, when few data are available. Some mathematical models based on Cost Evaluation Relationships (CERs) are available for a preliminary cost estimation. The most important method for the estimation of the Direct Operating Cost was developed by ATA in 1967 [1]. It is valid only for subsonic and sonic aircraft. In 1972, the NASA had modified this model, adapting it for hypersonic aircraft [2].
It is decided to use the NASA model to evaluate the DOCs of the LAPCAT A2, a hypersonic point-to-point vehicle with airbreathing engines, that European Space Agency is studying now. It is inside the project LAPACAT of European Space Agency, that studies the development propulsive strategies and their integration in a vehicle for the development of a hypersonic aircraft for the civil transportation. Before doing the DOCs estimation, the NASA equations have been analyzed carefully to understand the behavior of the drivers and to suggest possible alternative formulas that takes into account the most relevant technologies of hypersonic vehicle. It is developed a MATLAB tool that uses the NASA equations for making easier the evaluation of the direct operating costs for different operating scenarios and configurations of the aircraft.
The direct operating cost evaluation for a hypersonic vehicle is quite difficult for some reasons. One of them is the fact of there are not any hypersonic aircrafts on service. So, there are not reference data for comparing the results obtained with the mathematical model. The experimental data existing in this field are also few. This type of vehicle can have completely different configurations and profile mission. For this reason, it should pay attention to use a mathematical model that consider the features of the aircraft.

Another important aspect is to rewrite the NASA relationships for seeing the effect of the changes of some technological parameters. Analyzing the equations and the hypersonic data available, it is possible to see how the propulsive strategy and the aircraft configuration are influent in this field. The Breguet equation of the range is introduced in the NASA equations. It is an aeronautical equation for the evaluation of the cruise range, but it takes into account both aspects. The results of the modified equations are compared with the ones of the NASA method. The impact of technologies can be visible also on the acquisition costs of the vehicle. Some relationships are presented to express the acquisition prices as a function of design factors, as the maximum take-off weight or the thrust.

The evaluation of the direct operating costs requires some preliminary steps. Indeed, the first part of the thesis is the description of the life cycle costs of the aircraft. In particular the operating costs are examined deeper, because they are the subject of study. Some methods for the cost evaluation are briefly described. The main differences between the direct operating costs of a hypersonic vehicle and subsonic jet are shown. After that, there is an overview about the hypersonic aircrafts. The evolution of the hypersonic vehicle is described. The first hypersonic system was a missile, but now it is studying the project for the development of passengers' aircrafts. Before describing the LAPCAT project, the most important reference airplanes are exposed. They are prototypes or only studies about the development of hypersonic vehicle. After that, there is the description of the reference vehicle used for the cost estimation, the LAPCAT A2, and of the LAPCAT project. The main features of the aircraft are shown, giving particular attentions to the propulsive system.

Then, the mathematical models for the cost evaluation are shown. It is present a detailed description of the NASA cost evaluation relationships. They are a set of equations for the evaluation of the direct operating costs of hypersonic point-to-point vehicle. They are derived from aeronautical model for the DOCs estimation. The NASA model is used for the evaluation of the direct operating costs of the LAPCAT A2. The main difference between the DOC of subsonic aircraft and hypersonic aircraft are also considered in the description of the CERs.

Subsequently, it has a deep explanation of the NASA relationships under a technological point of view. For the equations of the direct operating cost of the fuel and of the maintenance, it is defined which are the technological drivers, that impact more on that cost items. In the case of the DOC of the fuel, it is analyzed the importance of the fuel price, because in the case of Liquid Hydrogen it can have sensible differences with the different productive scenarios. In the case of the equation of maintenance, it is analyzed the link between each term of equation using the QFD analysis tool. It is proposed an alternative form for the equation of the maintenance and of fuel with the introduction of the Breguet formula of the range. This one gives the possibility to evaluate the impact of the propulsive strategy and of the aerodynamic on the total DOCs. A mathematical expression for the evaluation of the acquisition costs is shown. It is linked with the technological drivers and it allows to consider the presence of the technological factors also in other cost items of the DOCS.

After that, the MATLAB tool for the cost evaluation is described. It is developed to help the user to do the cost estimation. It uses the equations of the NASA method to evaluate the direct operating costs. Thanks to the presence of graphical user interfaces, the inexpert users can use it easily. The tool also saves the data and the results on an Excel file giving the possibility to export them and to use other programs for the postprocessing.

At the end, there are the results of the direct operating costs evaluation for the LAPCAT A2. The results are compared with the ones of a civil aircraft to understand the main differences. The influence of the variation of the fuel price on the direct operating costs is also analyzed. Then, there are the results of the equations modified with the introduction of the Breguet formulation. They are compared with the costs obtained by using the NASA cost estimation relationships.

2. Aeronautical costs

The evaluation of the cost is very important in all field. When it has the development of a new product, the cost estimation is fundamental, because it gives the possibility to determine if what is created is competitive under an economic point of view and if it can have success.

In this chapter there is the description of the aeronautical costs and the methods to estimate the overall costs of an aircraft project. It is also considered the what happens for the hypersonic field, because the thesis is about the evaluation of the direct operating costs of hypersonic point-to-point vehicle.

Initially, there is a description of the aeronautical life cycle phases. There is the description of each stage of the aircraft program with some reference to the associated costs.

In the second section, there is the description of two method for evaluating the cost of project, the return of investment and the cost estimation relationships.

Subsequently, there is a description of the aeronautical Life Cycle Costs (LCCs). They are the costs of an aeronautical project from the first phase of the design to the disposal of the airplane.

Then, there is a deeper analysis about the operating cost, especially about Direct Operating Costs (DOCs) of a vehicle. Each cost item is examined to understand better which factors can impact on it.

After that, some mathematical method for the costs estimation are shown. Some of them are applicable in aeronautic flied. Other are useful for space systems and launchers.

At the end, it is present an analysis about the direct operating costs of a hypersonic aircrafts. It is done a qualitative analysis about the major changes required for this kind of vehicle than a subsonic aircraft.

2.1 Aeronautical life cycle phases

The increasing level of competitiveness that is currently characterizing the aeronautical market forces engineers to anticipate cost estimations at the very beginning of the design process. Indeed, the industry aims to maximize the profits coming from the difference between the price and the cost. The prices are the dollars paid by the customers to buy the aircraft. The cost is the overall amount spent for the resources used to manufacture the airplane [3]. Profit, price and cost have a different meaning according the different phases of the life cycle of the aircraft. They depend on the position on the economical process. For the airplane manufacturer the cost is amount of dollars spent to build the aircraft and the price is what they earn from the sale of the airplane. On the other hand, for the airline operators, the cost is made by both the price paid for the aircraft acquisition and by the dollars need to maintain it operating. The profit comes from selling services to the company's customers and it increases, if the operating costs are low. Both for airplane manufacturers and airplane operators, profits rise if the project is well made.

It is important to analyze the cost aspect from the beginning of the project because this is the point in which crucial decisions, with the highest effect on the total committed costs, are taken. These choices will affect all the next steps of the project.

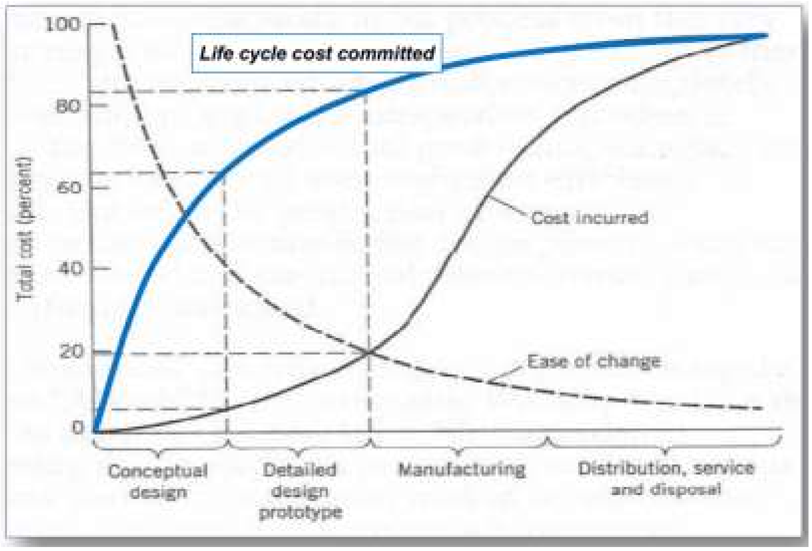


Figure 1: Life cycle cost committed [4]

Figure 1 gives the possibility to understand the importance of estimating cost from the beginning phase of project. The x-axis reports the overall life cycle of a generic aircraft from the design phase to the disposal. The y-axis shows the value of the costs of the vehicle as percentage of the total cost. The blue line represents the committed cost. In the conceptual design phase, where there is only the definition of architecture and of the major subsystems, the 60% of cost is allocated. This means that this preliminary activity has a remarkable effect on the subsequent phases of project, because fundamental decisions that influenced the overall project are taken. In this phase, the cost of manufacturing and equipping the aircraft are decided. This defines partially the costs of the subsequent phases. Competitive operating costs give to the airplane manufacturers the possibility to increase the number of customers and their profits.

The *black line* represents the cash flow, which is the disbursement expected in each phase. In the preliminary design phases, the cost required is low because the major impacting cost item is the salary of engineers and researchers. It is required a low quantity of material. In the manufacturing phase, the cost increases rapidly because there is the production of the aircraft. There is a larger number of workers involved than the previous phase and cost for the material growths. The *dotted line* shows the easiness to make change on the project. This characteristic diminishes all along the life cycle, revealing that after the conceptual and preliminary design phases, it is more difficult to make changes on the aircraft design. In the production phases, some parts can be different from the initial project. A change in this part of life cycle of the aircraft costs more than a modification during the previous phases. It is important to already know the cost in the conceptual design phase, even if it is difficult. The knowledge of the costs allows the designer to control them and to realize a project that gives to the industry and to the customer the highest profits as possible.

Airplane program is the evolution of an aircraft from the design to the disposal and it can be divided in the following phases, according to the reference [5]:

1. Planning and conceptual design:
   In this phase there is the mission specification to identify the major features that the airplane could have.
2. Preliminary design and system integration:
   The aircraft is designed according to the needs and the features previously identified. Trade studies are made to decide the right technological combination and the most “cost-effectiveness” design, because in this phase the cost analysis starts.
3. Detail and design development:
   In this phase there is complete integration between airplane and systems for the flight test and production certification.
4. Manufacturing and acquisition
   In this phase the aircraft is manufactured and delivered to the customer.
5. Operation and support:
   The airplane is acquired by the customer and it is operated with the help of accompanying support activities. This phase can be overlapped with the phase 4.
6. Disposal:
   This is the end of life of the airplane and it includes the activities for the destruction of airplane and disposing of material, which in turn can be sold. For military aircraft the disposal includes also the storage. Generally speaking, the disposal phase comes when the airplane’s technological and economical life finishes.

The airplane life cycle is made by these six phases. The costs associated to the life cycle are named Life cycle costs (LCCs). These costs are defined both for a civil aircraft and for a military one. In fact, as the aeronautical enterprise can be privately and/or government owned, the stakeholder of an aircraft design can be a private or the government (as military).

Figure 2 shows the life cycle costs for an airplane identifying the different phases of the project.

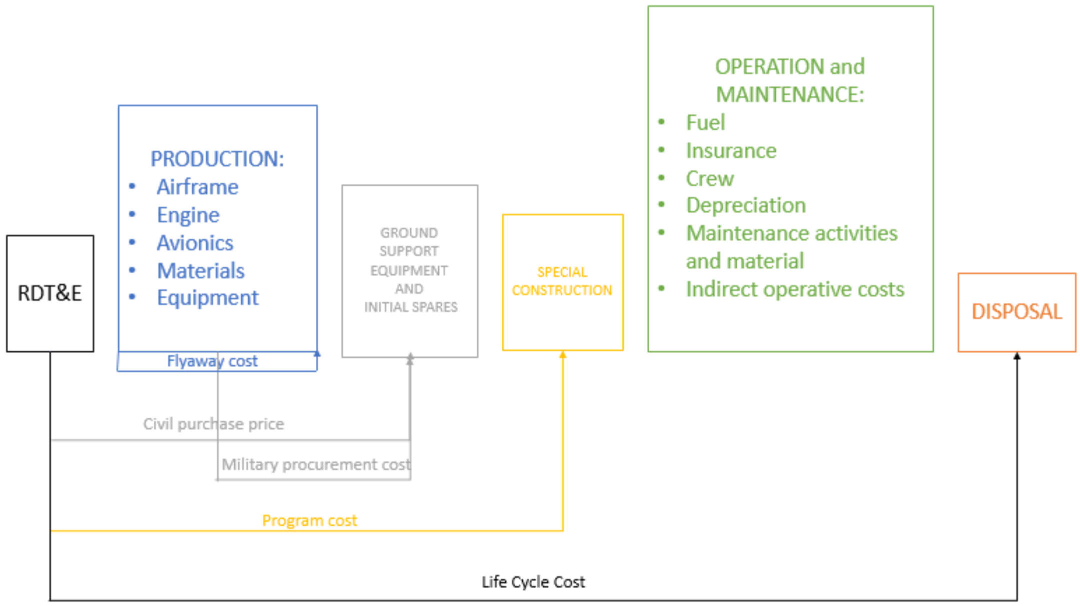


Figure 2: Life cycle cost.

For the purposes of this thesis, only costs for civil airplane will be considered. The Flyaway cost considers only the production costs of the aircraft for a single unit. For civil aircraft the Flyway cost is associated with the research and development cost, but for military aircraft it is considered separately alone because a government can pay separately in another contract the cost for research and development.

According to the reference [3], for a civil aircraft the life cycle costs are generally subdivided in:

- Research, development, test and evaluation costs (RDT&E):
  These costs are linked with the first three phases of the airplane program. They are related to the design and the tests of the aircraft. They start with the conceptual design phases and end with the production of the aircraft. These costs include the expenditure for the prototype and the testing machinery.
- Production (or procurement) costs:
  These costs consider the expenses required to build the airplane. In this costs item, there are the salary of the workers, the material and the infrastructure that should be built for the aircraft production. They can be divided in production costs and in ground support equipment costs. The first ones are the costs for producing and procuring the physical part of the aircraft and the material (Including the infrastructures). The second ones include the initial logistic support equipment, as data, training and initial spares. The production costs are a relevant part of aircraft final cost. This costs item is linked to the first part of the operating life of the aircraft.
- Operation and support costs:
  This cost is linked with the phase five of the airplane program, when the aircraft becomes operative. The manufacturers give a little support during this phase, but this is the cost managed by the airlines companies, which aim to reduce this cost as much as possible to maximize their profits. They include the cost of the crew, of maintenance and of repairable parts.

- Disposal costs:
  These costs are linked to the last phase of the airplane program. It is the cost due to the disposal of all parts of vehicle that can be destroyed or resold, as the case of the aluminum alloy. The end of life of a vehicle can be either an additional cost or a source of profits.

The life cycle cost can be also divide in acquisition costs and sustaining costs. The first ones are the costs associated with the first phases of the airplane program. They define the price that the customer should pay to buy the aircraft. The latter are the costs necessary to maintain the aircraft operative. They should be as lower as possible to increase the profits for the airline company. In this group, there are also the disposal costs.

In Figure 3, is possible to see the value of each part of life cycle costs.

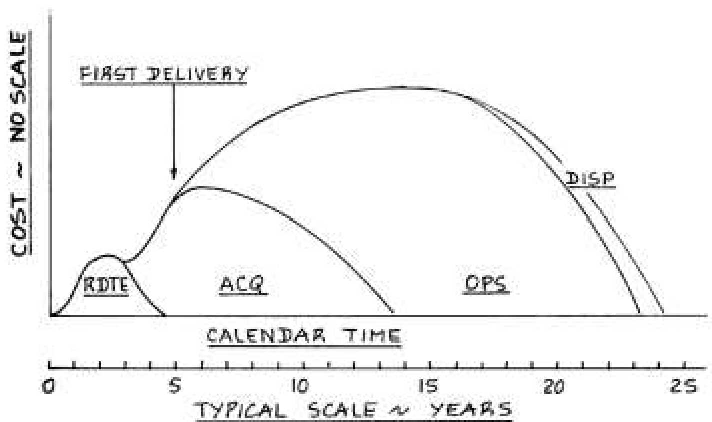


Figure 3: Schematic representation of life cycle cost history of typical airplane programs [3]

In the x-axis there is the life of vehicle, expressed in years, in the y-axis there is the cost of each phase. It can be seen that the most relevant costs item is the operating costs (OPS) that starts from the first delivery and ends with disposal, covering major part of airplane life. The disposal cost (DISP) has a little value compared to the other costs but it should be considered since the beginning of the project to take the maximum profit from the aircraft.

Another reason why carrying out costs estimation from the beginning phase of project is well shown by Figure 4

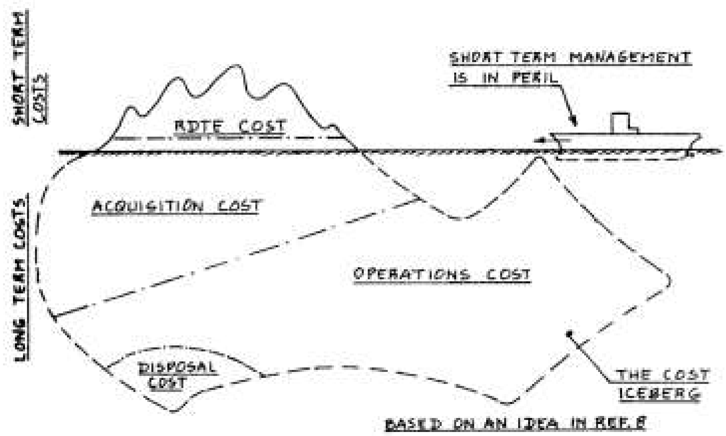


Figure 4: The iceberg effect in airplane program management [3].

The RDTE costs are short term costs, because they are the first that occur. One of the possible idea to reduce the life cycle costs of the aircraft could be decreasing this cost item. This is not correct because without a right investment in the research and development phase there will be an increase in the long-term costs, as the operational costs. This means that the costs sustained by the airplane company will be very high. The project manager is like the captain of a ship that is close to an iceberg: the danger is not only the visible ice over the sea (the short-term costs), but also the part under the sea (the long-term costs). The decisions taken in the preliminary design of project have a big effect on the aircraft life cycle cost, as it can be seen from Figure 1. The designers should be sure that the airplane is “cost-effective”, because if the acquisition and operating costs can be reduced, there will be many customers and their profits will increase. The project of an aircraft takes many years and inflation should be considered for estimating the “value of money” in the future. The profits cannot be the same every year due to taxation and economic crises so it is necessary to find a systematic way to estimate the life cycle costs already in the preliminary phases of project. It is important to minimize costs. To do that some important methodologies as Design-optimization, Design-to-price and Design-to-cost can be exploited, as suggested in the reference [3]. These methods act on the design variables and it is possible to identify the way to reduce the life cycle costs after a careful analysis.

2.2 Method for estimating aircraft costs

It is possible to use some different method for the evaluating of the if an aircraft can be a cost-effective product. In the following sections, two different way are shown. The first one is the Return of Investment (ROI). It is rarely used during the design phase, because it is difficult to apply. The latter is the method of Cost Estimation Relationships (CERs). It is based on a set of parametrical equations. The variables and coefficients depend on the features of the vehicle.

Return of Investment

The principal financial criterion to estimate the cost of the aircraft is the Return of investment of the manufacturing company. This is an economical variable linked to the operating costs. This parameter is very difficult to be used because is linked with the initial investment of an airline company to buy the vehicle.as depicted in Figure 5. In the first year of production there is a negative cost flow, because the customers do not pay the manufacturers. The return of investment comes after years when the aircraft is operative. For the manufacturers it is important to maximize the ROI for covering the building costs of the aircraft and for having greater profits. Figure 5 shows the cash flow history forecast conducted by McDonnel Douglas for the study of 150 passengers' regional aircraft.

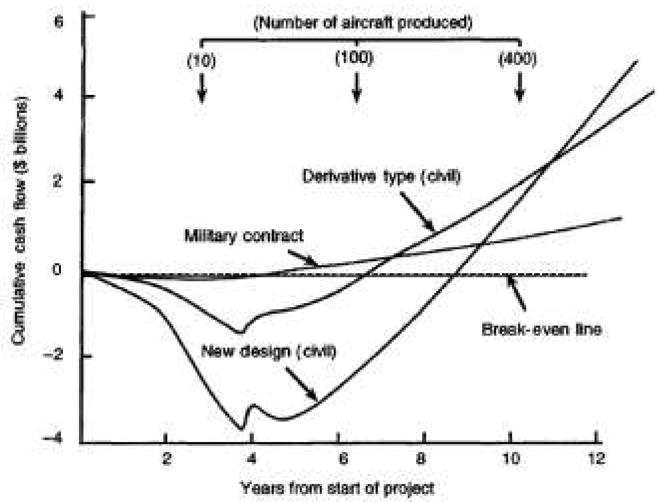


Figure 5: Project cash flow for 150 seat regional aircraft ($1995) [6]

Figure 5 shows how the return of investment depends on the number of airplanes produced.

The ROI is a parameter that is linked not only with the design and performances of the vehicle but also with the economic conditions. It can increase, if the economic situation is favorable. An important role is made by the customer, because they can decide or not to invest in a specific project comparing the features of the design and the performances of the aircraft with what other competitors can offer. As mentioned above, the life cycle costs estimation of a vehicle depends on the long timescale involved from the aircraft design to its disposal. Data for the economical estimation are usually about short-term cycle and this discourage possible customers. Great innovations are difficult to handle in the aeronautical industry. To validate them the manufacturers should spend time and moneys for the development and the certification. They could not be repaid because the investors could not have confidence in the new technologies and they need time to accept them.

Cost Estimation Relationships

The difficulties to use ROI for evaluating the total cost of the airplane brought to develop a different method for the life cycle costs analysis. It is possible to use the sum of the all cost items that are present in the airplane program. According to the phases of the project, there are different ways to estimate the cost parts. That's methodologies are shown in the Figure 6.

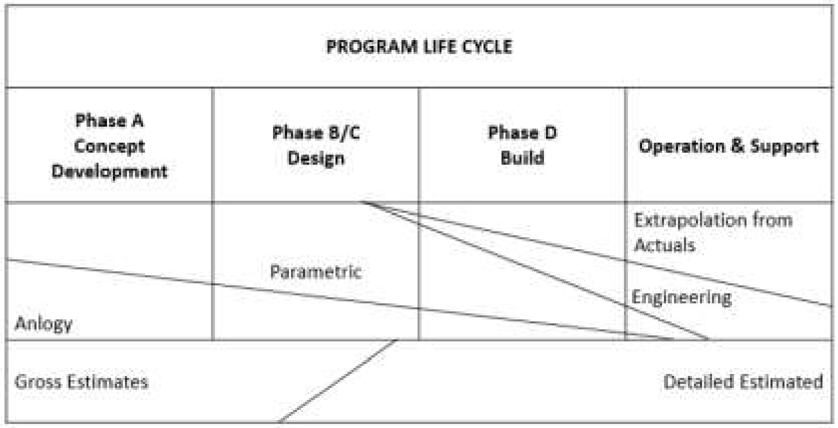


Figure 6: Different methodologies for cost's evaluation [7]

The different methodologies are:

- Analogy:
  Thanks to historical data of the company and using the cost of aircrafts with similar performances or characteristics, it is possible to identify the overall cost of the vehicle. This method is very simple and fast but it is applicable only in the in the first phases of project, where few data are available. A negative aspect is the very low level of confidence.
- Parametric or statistic:
  The cost estimation is based on database where parameters are inserted. Once the database is created, it is very easy to evaluate costs but the difficulties is to develop it. This method uses statistic equations based on some design parameters to estimate the cost of the aircraft.
- Engineering:
  It is a bottom-up approach where the activities are split to reach the most elementary level. This method is very reliable but laborious. The details requested for its implementation make it usable in the last phases of design. Using this method, the designer should know the working principles of each part and the time requested for its production.

The most used method at the beginning of aircraft design is based on the development Cost Estimating Relationships (CERs), statistical equations that are made from different coefficients linked to design variable This technique is used to estimate a particular cost item or price by using relationships between independent variables, called drivers [8]. The CERs are measurable relationships between the independent variable and the cost. The Cost Estimating Relationships can have the following shape:

$$Cost_i = Ai * W_i^B * X_i^C * Q^{-K} \qquad (1)$$

Where:

- A_i is a constant linked to the cost per kilogram of the different parts;
- W_i represents the dimensional features of the product (such as weight, dimensions, etc.)
- X_i is a performance characteristic of the component (such as power, speed, etc.)

- Q is the quantity of parts produced: if the number of parts built is greater, the cost is lower. This is called “Learning effect” and in Figure 9, it can be seen the Learning curves that describe this phenomenon.
- B, C, K are suitable exponents.

Equations like (1) do not predict the actual cost of the aircraft, but they give the users the possibility to compare different alternatives and to make the right decision to reach a “Cost-effective” product that can compete on the market.

2.3 Life Cycle Costs

From Roskam [3], it is possible to identify and analyzing the different elements of the life cycle costs.

The first cost item of LCCs is the RDTE cost. It is linked with the first three phases of the design and it covers all the expenditure of the activities needed from the planning to the conceptual design certification. It can normally be broken into seven cost categories:

1. Airframe and engineering and Design costs
2. Development support and testing cost
3. Flight test airplanes cost
4. Flight test operations cost
5. Test and simulation facilities cost
6. RDTE profit
7. Cost to finance the RDTE phases

All these elements can be evaluated with a mathematical relationship, such as the equation (1). Figure 7 shows the effect of the number of aircraft produced on the RDTE cost. In the x-axis there is the number of the airplanes built and the y-axis is the RDTE cost per vehicle produced. It can be noticed how the cost decreases with the increase of the units of aircraft built. It the case of the figure, the program has a financial sense only if 250 airplanes will be sold. Figure 7shows that the cost of RTDE phases can be repaid building and selling the greatest number of aircrafts.

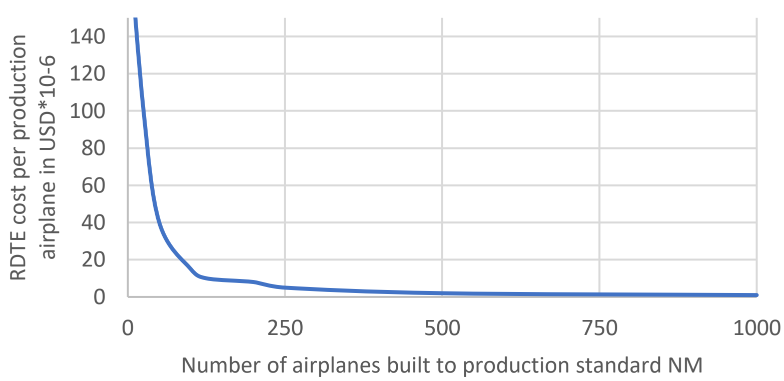


Figure 7: Effect of number of airplanes produced on the RDTE cost contribution per airplane (data from [3]).

The second item of aircraft life cycle costs is manufacturing and acquisition costs. The difference between acquisition cost and manufacturing cost is the profit made by the manufacturer. These costs depend on:

- The number of airplane built.
- The number of the aircraft acquired; this is percentage of the aircraft built, because the airline company can buy only few airplanes.
- The manufacturer profits.
- The cost of RTDTE program.

According to Roskam [3], the manufacturing cost can be broken into:

1. Airframe engineering and design cost
2. Airplane production cost
3. Production flight test operation cost
4. Cost of financing the manufacturing program

In the airplane program costs, there are the cost items relative to engine, avionics and interiors. Figure 8 shows how the cost of avionics is increased than the cost of mechanical equipment, airframe and engines for the military aircraft.   It has also the same trend for the civil aircrafts.

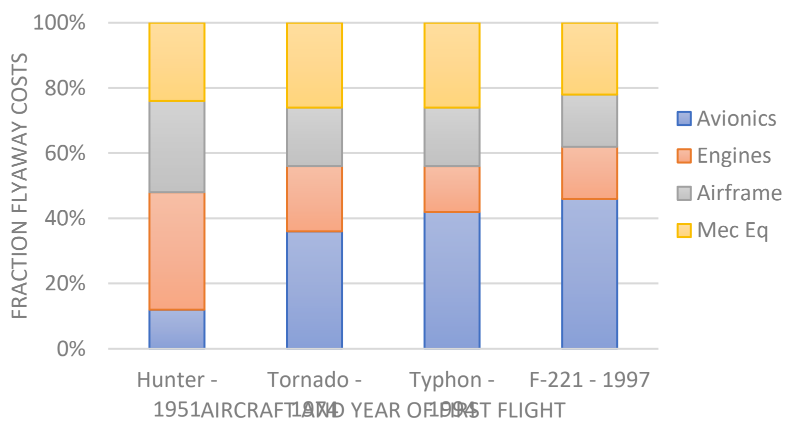


Figure 8: Trend of productive cost for different part of military aircraft (data from [4]*).*

The manufacturing cost depends on several parameters that are relevant to determine the airplane price. They are:

1. Airplane take-off weight.
2. Airplane design cruise speed
3. Total number of airplanes built
4. Airplane production rate
5. Airplane RDTE cost and the number of airplanes over which this cost is to be recovered

After reaching a certain number of airplanes built (as instance 200) there is reduction of the acquisition cost; this is due to:

- The “learning curve” effect.
- The hyperbolical decrease of RDTE cost with the number of airplane produced.

The decrease of the RDTE cost has been described previously using Figure 7. The learning curve effect is shown by Figure 9 . The learning curve effect means that with the increase of the number of aircraft produced, the workers gain in experience, reducing the time of production. This reduces the manhours required for the production of each vehicle and the production cost. The x-axis of the Figure 9 is the numbers of units produced. The y-axis is the relative unit costs. there are different curves on the figure. They consider different productive scenarios. According to the reference [5], if the production quantity becomes the double, the production costs per vehicle is reduced by a 20%. Usually, the airplanes production has the trend of the 75-85% learning curve. The production tends to reach a constant value, when the number of units produced becomes relevant.

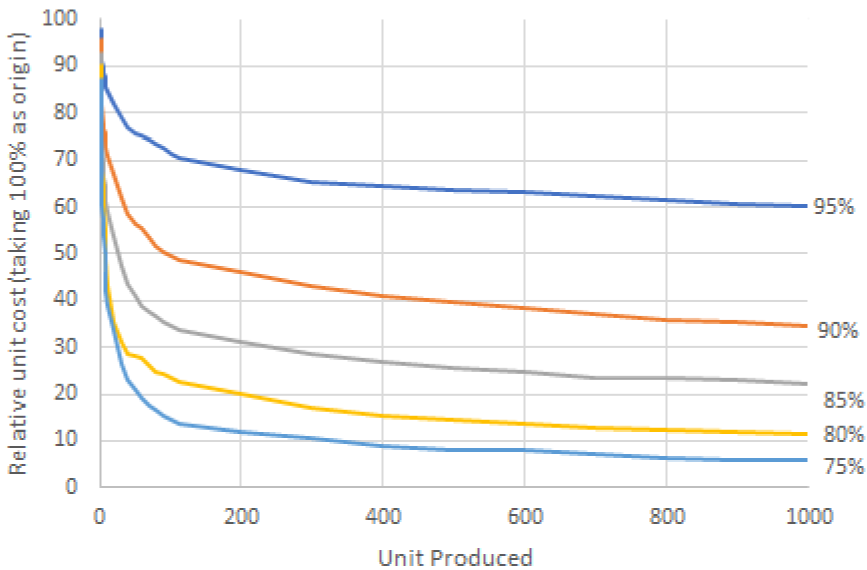


Figure 9: Production learning curve.

According to the reference [3], the learning curve effect can be expressed by the mathematical relationship:

$$MHRS_{per\ unit} = \frac{MHRS_1}{N_{program}^x}$$

Where:

- $MHRS_{per\ unit}$ is the required manhours per unit
- $MHRS_1$ is the manhours required to build the firs unit
- $N\_program$ is the number of airplanes built
- x is the learning curve exponent, that depends on the percentage of learning curve. Reference [5] gives the following equations to evaluate that exponent $2^x = 2 * \left(\frac{\%_{learning\ curve}}{100}\right)$

This effect shows how with the increasing of units produced, the numbers of manhours decreases thanks to the fact the workers gain experience. This reduces the hours of work for each airplane, thus reducing the cost.

According to the reference [3], there are some aircraft features that impact on the airplane estimated price. They are:

- Take-off weight.
  It is relevant when the number of airplanes built is small
- Cruise speed.
  If the airplane speed increases, it is possible to expect that the price of vehicle increases too, because it needs high-performances engines and materials. Obviously, the effect of the speed is greater when the number of the vehicle built is lower.

The most important but also difficult costs items to estimate is the Operating costs. This is mainly due to the fact that they are long-term costs and they are the biggest percentage of the total life cycle cost. These costs last for the entire operative life of the aircraft. The operating costs are linked to the economic variation because they consider also the cost of fuel. They are the most important cost items for the airline companies, that aim the operating costs are as lower as possible to maximize the profits. There are several different standardized methods that give the possibility to evaluate the operating costs. They do not give the actual cost of the aircraft, but they are useful to evaluate the different choices for developing a cost-effective project.

The operating costs of an aircraft are made by two parts:

- Direct operating costs (DOCs)
- Indirect operating cost (IOCs)

Usually, these two parts are considered separately because only the second one seems to have a direct link to the aircraft.

The indirect operating costs are not directly related to an aircraft type or to specified operations. According to the reference [6], the IOCs are composed of:

- Training (both for the crew and for the maintenance personnel)
- Customers service
- Public relations of cost expense of the airline companies
- Advertising, promotion and sales expenditures
- Administration and technical services
- Wages of the personnel (excluding the crew)
- Headquarters overheads
- Maintenance overheads
- Ground equipment miniatous costs
- Ground equipment depreciation
- Facility maintenance costs
- Facility leasing costs
- Facility purchase costs
- Facility depreciation

To identify the value of Indirect Operating Costs is important to know the airline policy about the aircrafts and traffic services, the promotion, the sales and the passengers' services. Data about general and administrative overheads ground property are necessary. In this cost item, ground equipment, maintenance of the facilities and their depreciation are also considered.

IOCs strongly depend on the activities and services that each airline companies offered. So, the IOCs can be very different from an operator to another one. It is difficult to estimate the impact of the aircraft design on this costs item, because even if it requires facility for maintenance it is not possible to link its costs directly to the vehicle. Airplane management and operational aspects are the most important factors and they may not be controlled by the aircraft designers. Usually if an airline company aims to be more competitive, it tends to reduce the indirect operating costs because they are more related to economic factors and not to the design of aircraft [3]. Some mathematical methods [6] propose to evaluate the IOCs as a percentage of DOCs. The indirect operating costs are between the 15% and the 50% of the total operating expenses according to reference [6].

It is very important to estimate the direct operating costs. The "Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes" (Air Transport Association of America, Dec. 1967) [1] is the first method that gives the possibility to evaluate the direct operating costs. All the other procedures to evaluates this cost items come from the reference [1].

The direct operating costs (DOC) can be associated with the aircraft. According to the reference [6], they are made by different components:

1. Standing charges
2. Flight costs
3. Maintenance costs
4. Financing costs

In Figure 10, it is possible to see all the elements that are part of the DOC.

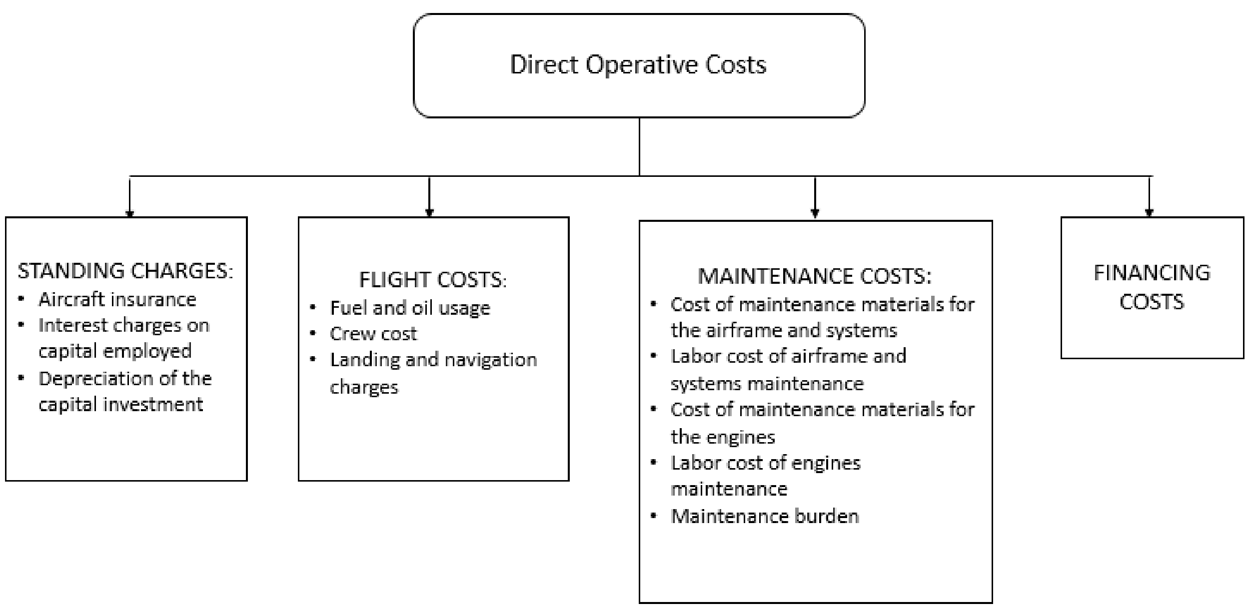


Figure 10: Direct operating cost components.

2.4 Description of the Direct Operating Costs

In this section, there is the description of the direct operating cost for a civil aircraft. They are divided according to the reference [6].

The first DOC item considered is the standing charges. They are not directly related to the aircraft but they regarded all the flight. They are:

1. Aircraft insurance
2. Interest charges on capital employed
3. Depreciation of the capital investment

The insurance cost covers:

- Flight and ground risk of airframe damage or total loss
- Passengers liability for death or injury
- Third part liability in case of death or injury
- Cargo damage risk

The operator can choose whether the insurance should cover all the damage to the structure or only a part according to the airline policy, but the safety should be guaranteed. The airworthiness authorities impose that the airline operator should respect the regulation for the aircraft insurance and the safety standards. Each year, the International Civil Organization published a safety report [9] where there are the guidelines for the insurance companies and the airline operators. The insurances companies evaluate the probability of the failures of the total aircraft system, even if the loss of the airplane could not happen for technical problems (as in the case of terrorism). The non-technical occurrence risks are difficult to estimate, but the insurance companies can change the insurance rate based on the mission and the airline security level. According to the [6], the annual premiums for a civil aircraft is between 1% to 3% of the aircraft price.

The insurance for the damage of the airframe depends on the hull loss rate. If the number of incident for a type of aircraft increases, the annual insurance cost is more, because it is more likely a severe damage for the vehicle. In Figure 11, it is possible to see the number of incidents for different type of aircraft from 1959 to 2016.

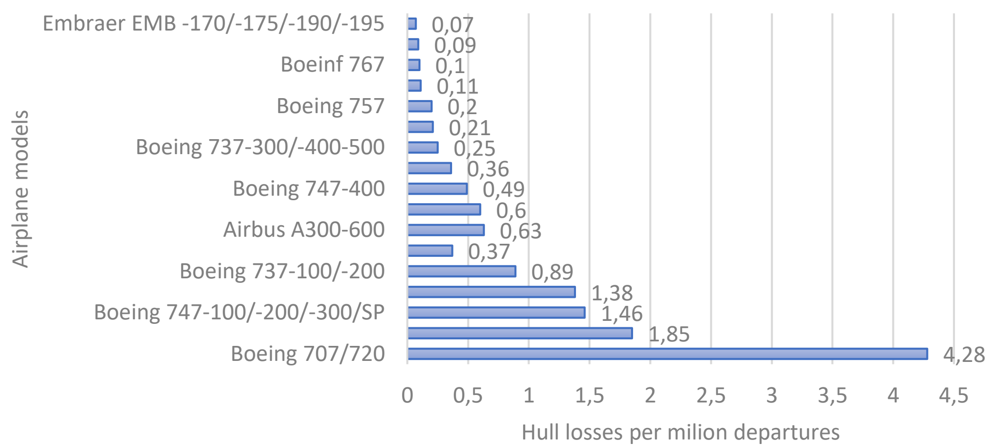


Figure 11: Aircraft hull loss fatal accident rate in worldwide commercial aviation, between 1959 and 2016 (data from [10]*)*

The second cost item is the interest charges. It is not possible to quantify them. They are related to the world economic climate, local exchange rate and the government choice to encourage the airline or the manufacturers. This cost item is outside the control of aircraft manufacturers. They are ignored in many methods of life cycle costs estimation, but it should be considered in any business plan of the airline company.

The depreciation is the most important part of the standing charges cost. It is linked to the capital involved, the airline purchasing policies, the accounting practices of the financial loan companies and the world economic conditions at the time the aircraft is bought. If the airplane is maintained in the airworthiness condition, it is possible to associate it a residual. The depreciation period can be estimated considering the time necessary to lose all the residual value.

This residual value decreases with the increasing of the aircraft aging. The depreciation period is decided by the economic plans of the company and by the development of the missions for which the aircraft are purchased. Typically, the useful life of an aircraft lasts 15-30 years and it has no residual value. In the reference [11], there are the depreciation period and the residual values decide by some airline companies. The depreciation period lasts 30 years at most. Increasing the depreciation life, the residual cost decreases. In fact, all the airline companies tend not to have a residual value for their aircraft. If a residual value is considered, it is less than the 10%. The depreciation rate is the value lost each year by the aircraft. It is around the 15% per year. The decision about the depreciation life and the residual value is made by the purchasing company and it depends on the total price of the aircraft. The price of the aircraft is difficult estimate, especially in the preliminary design phases, because it depends both on the airplane performances and on economic factors, as market conditions or the presence of competitors. According to the reference [6], it is possible to have a preliminary relationship between the weight of the aircraft and its price. The acquisition cost of the airplane increases with the weight, as it is possible to see in the Figure 12. The relationship has been obtained considering the operational empty weight of different aircrafts and their price. The airplane considered are some types of Boeing (B747, B777, B767, B757), some Airbus vehicle (A340, A310, A320), two McDonnell Douglas (MD11 and M90), the Fokker F70 and the British Aerospace 146.

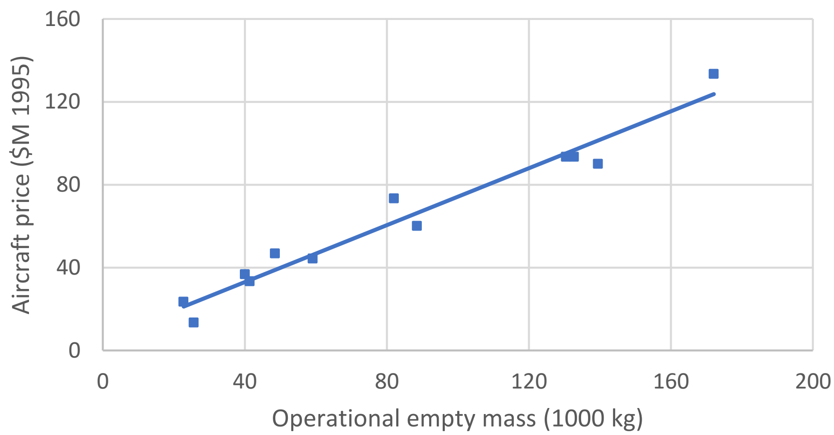


Figure 12: Aircraft price against operational empty weight (1995) (data from [5]*)*

Evaluating the price of the vehicle considering only the operational empty weight may lead to wrong results, because many other factors can impact on the price of the aircraft. The relationship between the price and the operational empty mas of Figure 12 is useful only for a first preliminary estimation. For more precise evaluations, high level methods based on the configurations and system details should be considered. Another way to estimate the acquisition price of the aircraft is to create a database with performances data of many airplane that could be used to estimate the price of the vehicle in a statistical way.

A relevant part of the DOC is the maintenance costs. The maintenance costs are items also of the IOC. In this case, the maintenance is related to the ground equipment. It is hard to evaluate the cost related to maintenance facilities, because sometimes they are a separated business not under the company control. For the direct operating costs, the maintenance is linked directly to the aircraft and its parts

Each cost estimation method has a different way to evaluate the maintenance costs. This causes a great variability of this relevant cost items. The fact that some airline companies contract out the engines and aircraft maintenance to specialized maintenance companies gives the possibility to define better the miniatous costs for each aircraft. In literature, few data are available about the maintenance. This does not make easy the creation of a database for estimating this cost item in a statistical way.

Maintenance DOC include the labor of the specialized personnel and the material costs for the spare parts and structures. The activity of the workers is not only to repair what is damage but also to do regular inspection to each part of the aircraft. Another aspect that makes the DOC of maintenance difficult to evaluate is the fact that each type of aircraft needs specific tasks for its maintenance. The great part of cost estimation method usually divides the CERs for evaluating separately the contribution due to the airframe and to the engines. In each case, there are two different mathematical relationships for considering the material needed for the maintenance and the labor required. The total DOC of maintenance is due to these five parts:

1. Cost of maintenance materials for the airframe and systems
2. Labor cost of airframe and systems maintenance
3. Cost of maintenance materials for the engines
4. Labor cost of engines maintenance
5. Maintenance burden

Figure 13 shows the composition of total maintenance costs where it can be noticed that the total maintenance cost can be divided in three parts that have more or less the same value in percentage. The airframe and the engine maintenance activities are the most important under an economic point of view. In Figure 13 is considered the contribute of the maintenance labor and of the maintenance materials.

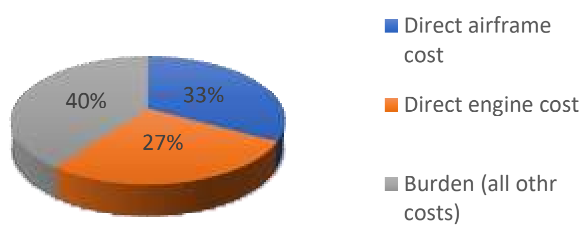


Figure 13: Average Composition of total maintenance Costs (data from [12]*)*

Table *1* comes from Roskam [3] . It shows the manhours necessary per flight hours for different types of airplanes. The data are not recent, but it is interesting to see how the maintenance manhours increase with the utilization of the aircraft.

	Annual utilization in flight hours	Maintenance Manhours per Flight hours	Data from years
Cessna 150	250	0.3	1974
Cessna Skywagon	250	0.5	1974
Beech Kingair 90	350	1	1974
Cessna Citation I	400	3	1974
McDD DC-9-30	2900	6.4	1973
B-707-300	3196	8.4	1973
B-727-200	2670	7.9	1973
B-737-200	2800	6.5	1973
B-747-100	2200	6.6	1973
B-747-100	3525	14.5	1973
L-1011	1870	14.1	1973
McDD DC-10-10	2450	10.9	1973

Table 1: Maintenance manhour data for commercial airplanes (data from [3]*).*

The distribution of manhours between engines and airframe depends on the type of airplane and the engine features.

According to the reference [3], some features of the engine and of the airframe can have effect on the maintenance manhours. They are:

- The airframe weight;
  the manhours required increases with the weight of the airframe because there are more parts to check and to repair.
- The airframe prices;
  the cost of the airframe describes the properties of the material. New materials have higher cost and required more or most accurate maintenance activities. This increase the value of the cost item.
- The engine's thrust;
  the maintenance required increases with the thrust, because the engines have high level performances.
- Engine prices;
  as in the case of the airframe price, the engine price is linked with the performances of the engines. If there is a high-level propulsion system, the maintenance should be more accurate and its cost increase. Generally speaking, it is clear that as more expensive is the engine, the quality of the material used for maintenance is higher and the price of maintenance activities growths.

The flight costs are another item of the DOC. These costs are directly linked to the flight. They are:

1. Fuel and oil usage
2. Crew cost
3. Landing and navigation charges

The cost of fuel is one of the most significant components of the operating costs. Figure 14 shows the historical impact of the fuel price on the DOCs. In the x-axis there is fuel efficiency and in the y-axis, there is the fuel cost. Both are divided for the RPK, revenue passenger per kilometer. Increasing the propulsive efficiency there is a reduction of the direct operating costs. If the fuel price increases, the DOCs have the same trend.

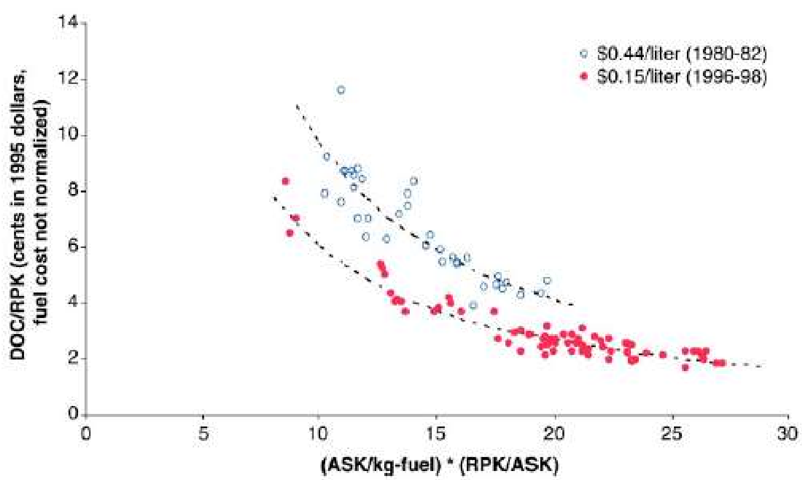


Figure 14: Effect of fuel price on the direct operating cost (DOC)—fuel efficiency [13]

It is not easy to evaluate the cost of fuel for the future years, because it strongly depends on the economic variation of the markets. In Figure 15, it is possible to see how variable is the jet fuel price. In the x-axis there are the months for which it is evaluated the fuel price, that is in the y-axis. It is possible to see how instable is the fuel cost for barrel. Its value changes rapidly from a month to another.

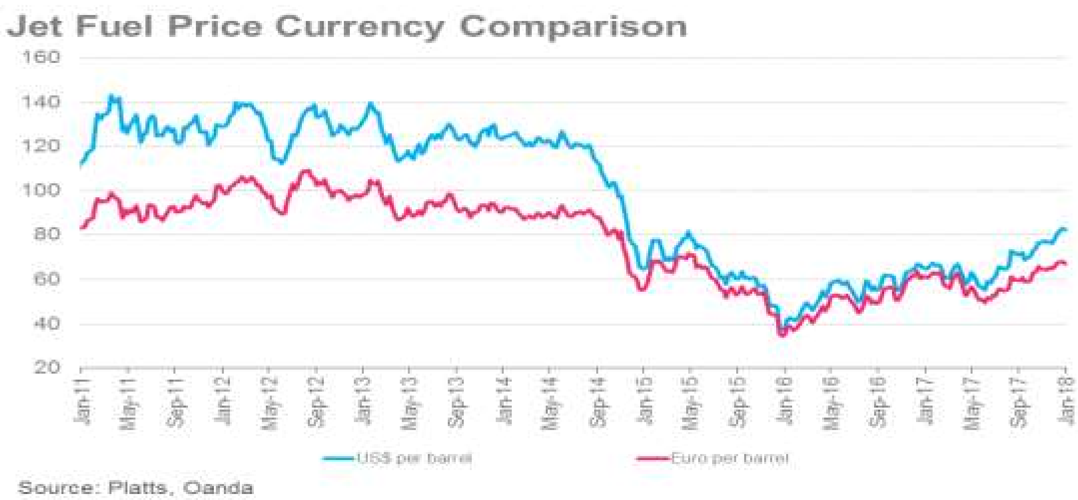


Figure 15: Fuel cost between 2011 to 2018 [14]

The crew cost is linked to the wages of the flight crew (that is the pilots), because the flight attendant salaries are in indirect operating cost as passengers' services. Typically, the flight crew is made by two pilots, according to airworthiness standards and labor union agreements. The utilization of the crew depends on the contract and it normally is 800 hours per year for a medium size regional jet aircraft, according to the reference [6]. The wages are very different for each airline company. For the DOC evaluation it is useful to use a medium value. The crew cost considers also extras such as overheads for enforced stop-overs on long range, that sometimes are considered as indirect operating cost. The wages of the crew's members increase according to:

- The role (captain or co-pilot)
- Equipment flown (the salary increases its value with airplane's speed and weight)
- Seniority
- Union and company rules

The Figure 16 shows the average annual crew's salary for some American airlines. As told said before, there can be great differences between one company to another.

The DOC of the crew considers the total cost of the cockpit. It includes the benefits, the cost of the training activities and the travel expenditures of the pilots. Usually the crew is made by two people, the pilot and the co-pilot. The legislation gives the rules about the number of hours they can fly per month and the hours of rest. It suggests the presence of a third person in the case of long mission [9].

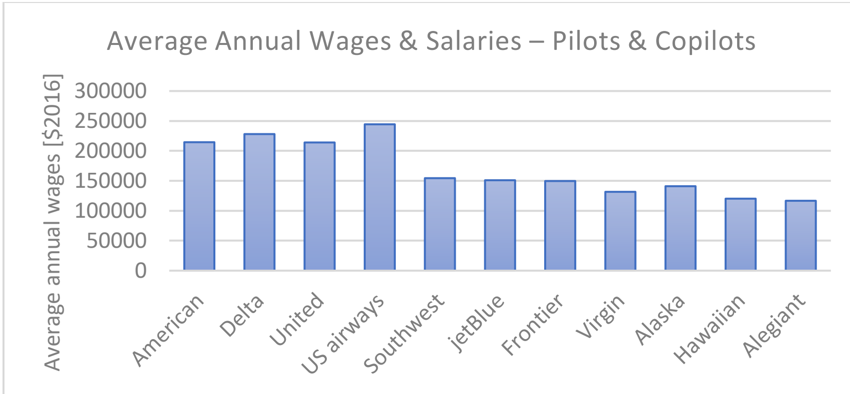


Figure 16: Average annual wage and salaries - Pilot & Copilot (2016) (data from [15]*)*

Another item of direct operating cost are the Financing costs. It is difficult to estimate them, because they are related on how the companies decide to finance his airplanes' fleet. The operators can borrow money to acquire the aircraft or the spare parts or it can lease some of its equipment. If they invest their own money, also the interests should be considered. A simple way to estimate these cost items is the "Rules-of-thumb" that is derived from financial observation. It says that the financing costs are the 70% of the total direct operating costs [3].

For a civil aircraft, typical breakdown of the direct operating costs and percentages of the items are shown in Figure 17.

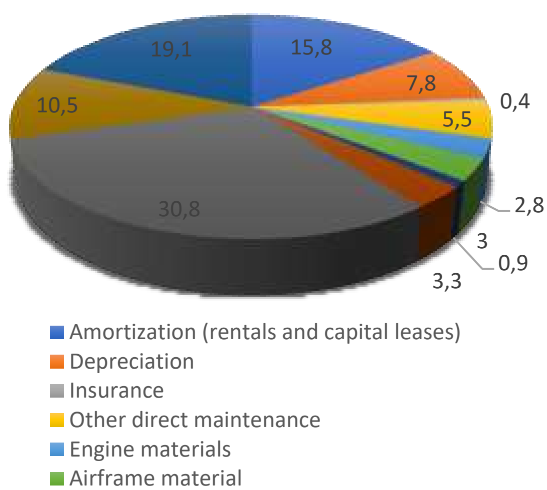


Figure 17: Typical DOC+I Composition (10 major U.S. airlines during 1992-98) (data from [13]*)*

In Figure 18 it is shown the evolution of DOC from 1968 to 1998. In the x-axis there is the years and in the y-axis at the left side, there is the value of the DOC. In the right side there is the fuel price. The trend of the fuel price is described by the black line. For the DOC, it is interesting to see how the fuel is the most important cost item. The direct operating costs are increased in the last few decades and each cost item has grown. The insurance cost has less impact on direct operating costs.

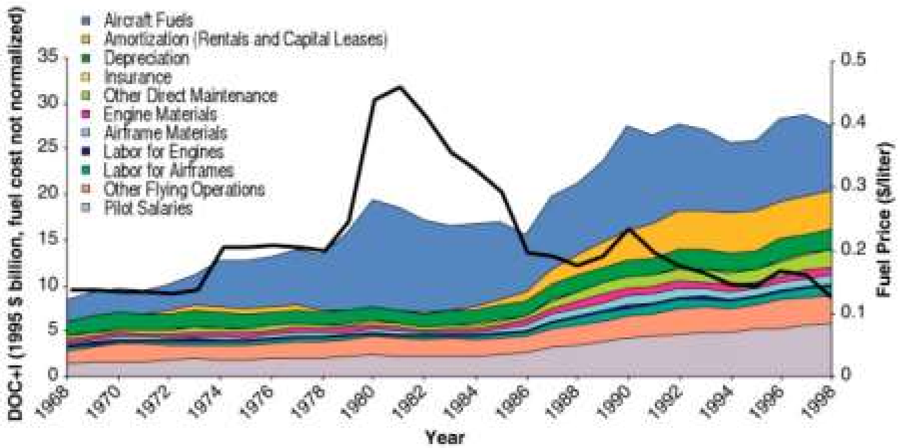


Figure 18: Evolution of investment and direct operating costs (DOC C I) for 10 major US [13]

The data of the reference [3] underlines that some factor can impact on the direct operating costs:

- If the block distance increase, there is a strong reduction of the DOCs. The block distance is the distance flown by the aircraft, considering also the taxy phases before and after the flight.
- The crew salary and the cost of cockpit have a weak effect on the direct operating costs.
- The fuel price has a strong effect on the DOC. If it increases, they have the same trend, because the fuel cost is the most important cost item.
- It is also relevant the maintenance manhours required by the aircraft. If it is required a big effort for the maintenance, the direct operating costs increase.

For civil aviation, it easy to understand that the major cost item is the operating costs that represent the 86% of the total vehicle life cycle cost [3]. The RDTE costs are less important but they are fundamental to guarantee the development of the best aircraft as possible under all standpoints and especially under the economic aspect. What it is decide in the phase of project has a great resonance on all airplane program and can have a great effect on the all life cycle cost. Figure 19 shows the percentage of each cost items of the life cycle costs. There are not the disposal costs that can be the 5% of the total life cycle costs.

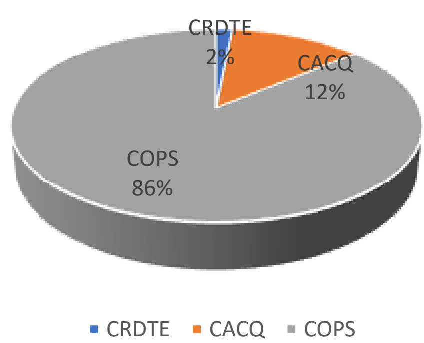


Figure 19: Life cycle cost of airplane program (data from Roskam [3]*)*

2.5 Mathematical models for the Direct Operating Costs' evaluation

For an airlines company that buys a new aircraft the most relevant cost items are the operating costs. As it has been anticipated in the previous chapters, the operating costs can be split into:

- Direct Operating Costs, DOCs
- Indirect Operating Costs, IOCs

The first ones are directly linked to the aircraft used while the second ones depend on the management and on the choice of the airline company. The profit of company increases if the operating costs, and in particular the direct ones, can be reduced.

The designers should develop an aircraft considering these costs, to attract the customers and financing their project. This evaluation becomes more important in the case of hypersonic aircraft, because none of them is now operating and the comparison with a traditional aircraft could be difficult, and the exploitation of pure statistical approaches may lead to erroneous results. Thus, it is necessary to develop a mathematical model that gives the possibility to do a plausible estimation of the direct operating costs, considering the major technical features of the hypersonic aircraft. It should be useful not only for a specific project, but it should provide correct results for different types of hypersonic aircraft.

Some mathematical models for the direct operating costs evaluation have been developed for both the aeronautical field and the space one. It is chosen to explain briefly both the aeronautical model and the space models, because a hypersonic aircraft has some features closed to the space technologies, others similar to aeronautical devices.

The models considered as references are:

- Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes (Air Transport Association of America, Dec. 1967) [1]
- The Roskam Model [16]
- NASA methodology for hypersonic transport technology planning [17]
- NASA Cost Estimating Handbook [7]
- TransCost model [18]

The Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes [1] is a basic methodology for the cos estimation developed by ATA, Air Transport Association of America. The edition of reference is the 1967. These equations were updated annually by the aircraft manufacturers. This method is the first standardized method for the evaluation of the operating cost of subsonic jet and all the other methods use this one as reference.

In the part 8 of Roskam Airplane Design [16], there is the evaluation of the life cycle costs for civil and military airplanes. This method can be used only for traditional aircraft and it based on the previous ATA method. It requires some economic features and performances of the aircraft to do the estimation. The method uses some simple formulas for obtaining some values difficult to knows, as the acquisition costs. In some situations, there are some curves for different aircraft. They give the possibility to evaluate complex coefficients knowing basic features of the vehicle.

The NASA Cost Estimating Handbook aimed to be a guide of costs estimating for NASA programs. It gives the possibility to evaluate which NASA program can go to a further life-cycle phases. It gives information about the costs risk of a project, cost alternatives within the projects and information to make resource allocation decisions. This permits to control the resources available, avoiding waste of money. In the *Table 2*, it is shown the NASA cost estimating process. The methodology for the cost estimation can be the analogy (with references programs), the Parametric methodology (using equation based on a database made by references programs) and Engineering methodology (it is a buildup way to evaluate the total cost knowing the cost of the single parts). The choice of one methodology depends on which phase the program is and the data available.

Part 1: Project Definition Tasks	**Part 2: Cost Methodology Tasks**	**Part3: Cost Estimating Tasks**
1. Receive Customer Request and Understand the Project	4. Develop Ground Rules and Assumptions	8. Develop the Cost Estimate
2. Build or Obtain a Work Breakdown Structure (WBS)	5. Select Cost Estimating Methodology	9. Develop and Incorporate the Cost Risk Assessment
3. Define or Obtain the Project Technical Description	6. Select/Build Cost Model/Tool	10. Document the Cost Estimate
	7. Gather and Normalize Data	11. Present the Cost Estimate Results
		12. Update the Cost Estimate Required

Table 2: NASA Cost Estimating Process [5].

The TransCost Model is described in the refence [18]. It uses historical data from conventional launch system to evaluate the cost of future reusable launcher. The evaluation is done with the development of simple cost evaluation relationships, based on the physic features and the performances of the launcher.

The last model was the NASA methodology for hypersonic transport technology planning. It is developed in 1972. It is a modified version of the ATA method for the hypersonic aircraft. The objective of the study was to evaluate the costs of hypersonic aircraft considering some technological parameters. The costs considered were only direct operating costs, defined as in the ATA model.

This last model is considered as reference model for this work because it was properly modified for the hypersonic case. The study also gives the value of some coefficient difficult to know at the preliminary phases of the project, giving the possibility to do a preliminary estimation. Obviously, the equations are relative to the seventies and some parameters should be updated or modified.

2.6 Cost Estimation for hypersonic aircraft

The future of the civil aviation is the hypersonic aircrafts. They are a completely new field. There are only research programs that are evaluating the possibility to design and built this new type of vehicles.

For the hypersonic aircraft the items of the Life cycle cost can be the same of a subsonic jet. What changes is their value. Indeed, the most important challenge for introducing the hypersonic vehicle in the civil aviation is to develop an aircraft that can compete with a traditional one under the economic point of view.

Most of the hypersonic technologies are in form of prototype and they should be tested. For evaluate the development of a new technology, it is used the TRL, Technology Reediness Level. It is a method to evaluate the technological maturity of the critical elements. It is based on a scale from one to nine, where one means that the technology is under research phases, and nine means that it is ready to be used. For passing throughout each level the new technology should be studied and prototypes should be built and tested. This is increase the RDTE cost of hypersonic aircraft than a traditional one. This cost item probably continues to be the lower percentage of total life cycle costs. Especially the first time the research and development phase takes more time, but it should be taken on in the best way as possible. In fact, as said before, during this phase there are the first cost estimations that are necessary to create an aircraft program competitive under an economic point of view. During this phase of the program all the possible configuration and production choice are made. To make a mistake in this part has a great effect on all the future phases. It is interesting to evaluate the changes in the life cycle cost for this new king of aircrafts. The focus is on the operating costs. The RDTE phases is the same of a traditional aircraft, because a team of designers and experts in various field defines the possible configurations and features of the hypersonic vehicle.

The cost of production will be greater, especially at the beginning because the number of aircraft will be small and the manufacturers will not have the right experience. To avoid inconvenient that can stop the production or increase the costs, it is important that during the RDTE phases all the aspects have been evaluated. Under the point of view of the manufacturing costs, what is very evident is the employment of new materials that should be suitable for the high-level performances of the aircraft. Probably, they need new working techniques that increase their price and maintenance effort.

As said in the previous parts, the disposal cost ca not be underestimated in all project, but in particular in the case of airplane program that required a high initial investment and that has high cost.

The operating costs can determine the success of a hypersonic aircraft. A right evaluation of this cost items is important just at the beginning phases of the project. There are not hypersonic aircraft operative. The data available are few and comes from prototype. This does not give the possibility to create a database. It is not possible make a comparison with a subsonic aircraft. The operating costs are the most impacted items because they considered many aspects that can be modified by an innovative project.

In this section it is done a qualitative evaluation about how the operating costs can change, the attention is mainly on the DOCs, because the IOCs are strongly depended on the policy and on the organization of the airline company.

For the Indirect Operating Costs, it can be seen how the infrastructures required to maintain this type of aircraft operative and to guarantee its right maintenance may not be the same of the traditional aircraft. This because the dimensions of hypersonic aircraft are bigger and the airplane configuration is not the same of a civil one. These new aircrafts may use cryogenic fuels, as Liquid hydrogen, so the airport should be properly equipped and the company should be able to manage its transport and use. Another important aspect that should be considered it is the wages of service personnel, in particular of the flight attendants.

If they are on board, they required a higher wage, because the mission it is different from traditional aircraft. The indirect operating cost of a hypersonic vehicle should be higher than the ones of subsonic jet.

For the DOC all the items change their value.

The most interesting hypersonic project is the LAPCAT [19]. It is an ESA study, that aims to design a hypersonic aircraft able to flight at Mach 8. It is a hypersonic vehicle that uses air breathing engine. This is not the only possibility. Others European studies, as a SpaceLiner [20], aim to develop other concepts of hypersonic aircraft. One of the them uses rocket engines the desired altitude. After that, it has a parabolic flight for reaching the destination point. The mission is one of the factor that can influence the DOCs, because the different performance required new technologies. This increases the price of the aircraft and the cost of its materials. This reflects on a different cost of maintenance. The fuel deigned for the hypersonic mission is LH2. It has a different price than the hydrocarbons. Currently it is more expensive. It will be reduced in the future, but the only data come from research and can not consider the economic trend. The cost of crew depends also on the performance of the aircraft. For some aspects, the hypersonic vehicles are close to the space field. It is possible that the hourly cost of the cockpit increases, considering also the presence of a second co-pilot. The heat load during the flight is so high. It causes the deterioration of the structure but it also slows down the ground operation. This aspect should be considered and can have a great impact on the block time and od the costs of vehicle.

The structural configuration of the hypersonic aircraft is different than the one of the subsonic jet. One of the great challenges is to develop a waverider configuration. In this case, the aircraft uses the shock wave generated by the hypersonic flight, to add lift and to increase its aerodynamic performances. The manufacturing costs can be influenced by this aspect, because it is required a high-level preparation to the workers. The depreciation cost is different, because new technologies and configuration lose their value more rapidly.

For some aspects the hypersonic aircraft are closer to space vehicle. The mission has the features of space one because of its altitude and speed This aspect and the low level of confidence can increase the insurance costs, both to cover the damages to the structures and to guarantee the safety of the passengers.

		TREND
STANDING CHARGES	Aircraft Insurance	↑
	Depreciation cost	↑
FLIGT COSTS	Fuel and oil	↑
	Crew cost	↑
	Landing and navigation charges	↔
MAINTENANCE COSTS	Maintenance of engine (labor and material)	↑
	Maintenance of airframe (labor and material)	↑
	Maintenance Burden	↑
FINANCING COSTS		↑

Table 3: Trend of the Direct Operating Costs of a hypersonic aircraft compared to a subsonic airplane

Table *3* shows the possible trend of the direct operating costs for a hypersonic aircraft. All the items increase due to the peculiarity of this new kind of vehicle.

The greatest cost item should be the cost of fuel. These vehicles required big amount of fuel to reach their performances. Some studies [19] underline as the fuel weight is about a half of the maximum take-off weight. The impact of the depreciation is more evident, because the shorter depreciation life grows this cost item. The cost of crew is bigger than the subsonic but it has a minimum impact on the direct operating costs, as it happens in the case of subsonic jet. The maintenance costs are the most relevant in the case of traditional aircraft. In the case of hypersonic aircrafts, its effect is very restrained by the fuel cost.

Few data are available for the hypersonic aircraft and in particular all the economic references are absent because all the new technologies are only in a research phase. This is a great obstacle for developing cost estimation method. The results that will be obtained with a cost estimation are not comparable with anything to evaluate whether they are right and to consider the possible corrections.

A right cost estimation in the preliminary phases of the design is important for traditional aircraft projects. It is fundamental for highly innovative design as it is a hypersonic aircraft. It can attract both investors and customers that aim to gain the higher profit as possible from what could be the future of aviation.

Under the aspect of technological research, the hypersonic world is full of sources, as the development of airbreathing propulsion systems. They make these futuristic vehicles closer to a traditional airplane. Another important aspect is the new high-level materials, that should withstand great thermal loads in cruise. To develop a vehicle, that is able to achieve the highest number of flight cycles per year, is the key of success for the economic efficiency. Another aspect is trying to use the infrastructures that are used for traditional aircraft, as the airport. It is not possible using all that it is in an airport today. The runways should be changed, because the first studies show that these aircrafts are heavier than a traditional jet and they need longer runways for take-off and landing [19]. The vehicles are equipped with cryogenic fuels and after the flight the external skin surface are hot for the high thermal load. It is not conceivable doing the same operations of a traditional subsonic jet.

Another aspect that should be changed is the certification. Now, it is very early to think about it but it should be evaluated by the time the first prototypes are ready to flight. It could be derived from the existing certification or it could be rebuilt for this new type of aircrafts, like for the Concorde. Particular aspects are the risks linked to these new vehicles, that should be evaluated with a design team, avoiding making the project unfeasible.

3. Overview of hypersonic initiatives

The objective of the thesis is the evaluation of the direct operating cost of hypersonic aircraft. For this reason, in this chapter there is an introduction and a description of the main aspects of the hypersonic aircrafts.

This chapter aims at presenting an overview of the major initiatives in the field of hypersonic speed. In particular, after discussing the main reasons why hypersonic transportation systems are currently so interesting, some historical notes of their developments are presented. Then, a specific focus on the LAPCAR A2 is done.

After that, the most important hypersonic vehicles are presented. All of them have given the possibility to understand better the characteristics of the hypersonic flight. They can be considered the reference vehicles for the vehicle used for the cost estimation, the LAPCAT A2. They were chosen because of their technical features and configurations. The type of mission is another important aspect that was evaluated.

In the fourth section of this chapter, there is the description of the aircraft used for the DOCs estimation, the LAPCAT A2. This aircraft is a part of the LAPCAT project. It is an ESA project that aims to study and develop different configurations of hypersonic point-to-pint vehicles. The technology that drive all the program is the propulsive system. The European Space agency aims to use only airbreathing engines to reach hypersonic speed. In this section there is also the description of the LAPCAT MR2. It is another hypersonic vehicle inside the project LAPCAT that can be considered an “evolution” of the LAPCAT A2.

At last, in this chapter, there is a description of which aspects are different between three subsonic jet and the hypersonic aircraft. This section is useful to understand which aspect should be modified or analyzed better when it is decided to use mathematical model for the cost evaluation

3.1 Introduction to hypersonic aircrafts

The air traffic continually grows without stops from the beginning of commercial aviation history until today. This rise has been strong even when the period was not good (as after the 11Th September attacks or after the economic crisis). The reference [21] underlines as the greatest growth in the air transport is now in the Asian-Pacific region, where there are emerging powers, as China or India. This is due to the increase of their explosive economic power and the presence of large areas that can be reached more easily by the plane. It is possible to analyze the trend future worldwide air traffic in Figure 20, where there is the increase of the air traffic, measured as Revenue Passenger Kilometers (RPK), throughout the years, considering both the domestic and the international flight. The forecasts show how the both type of flight will increase in the next twenty years. It is interesting the evolution of the international flight, because the development of hypersonic aircraft has sense only for long-haul routes.

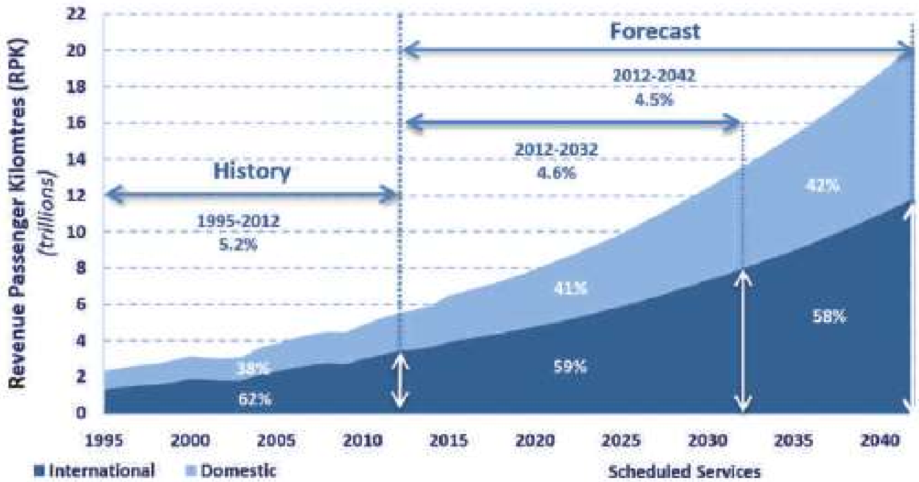


Figure 20:Total passenger traffic: history and forecasts [21].

A great impulse to the worldwide air traffic is expected by the capability of reaching hypersonic speed and giving to a wide number of passengers the possibility to reach the other side of the world in few hours. Currently, the flight time of intercontinental routes connecting the major cities is sixteen hours at least and of course, the dramatic reduction of traveling time will make these routes more interesting, inflating the number of possible tickets to be sold.

According to the definition, a hypersonic aircraft flies with a cruise Mach number greater than five. The term was used with this meaning for the first time by Husue-Shen Tien in 1946 [22]. He worked as aerodynamicist at the California Institute of Technology. Hypersonic vehicle can be considered as the future of commercial aviation and a first step towards space vehicle". The mission of these vehicles is not so different from a traditional transportation one, connecting city pairs bringing passengers and more in general payload respecting the airworthiness regulation. With the aim of reducing the operating cost, the idea is to exploit existing airports, with the necessary improvements, of course.

However, the very high cruise speed as well as the consequent thermal loads that the structure shall withstand, make the hypersonic airplane closer to a space vehicle, also from the point of view of the required on-board subsystems.

The use of such innovative vehicles is convenient for the long routes, reducing by more than a half the time of flight. This can start a new era of long-haul travel, that can change the economy of the airlines and of airport, but especially the way of travel.

The key of success is to give the possibility to use this type of flight to a wider range of passengers and this can happen only with a reduction of costs. As it has been said in the previous chapter, cost estimation should be carried out since the very first preliminary phases of the project, guaranteeing the economic feasibility of the entire Lifecycle. For hypersonic vehicles, preliminary cost estimations will reveal very expensive technologies and potential cost increases due to some non-reusable components. All these aspects can have detrimental effects on the operating costs, preventing investors to fund these too risky activities and for this reason, special attention should be devoted to find out strategies to reduce them.

3.2 Typical mission profiles

The most typical mission profile involving hypersonic speed legs is the point-to-point transportation that makes faster to fly from two opposite parts of the world. However, in literature, suborbital flights are sometimes mentioned. Besides, it is very rare that hypersonic speed would be reached in these missions, they are considered as test-bed of technologies enabling for hypersonic speed.

Suborbital parabolic flight

Some private companies are studying the suborbital parabolic flight. This type of hypersonic mission is interesting under different point of view. One of them is the possibility to open the market of the space tourism. Another one is the possibility to do test in the condition of microgravity.

The mission profile, shown in Figure 21, is made by different segment. After a phase of flight at constant altitude, the aircraft start to fight higher. In this phase there is an acceleration of 1.8g. After that there is the maneuver of "injection", where the aircraft trajectory is like a parabola and the engine thrust is reduced. The vertical load factor goes to zero gravity for about twenty seconds. After that there is a flight phase at 1.8g, symmetrical to the previous one. Subsequently the airplane flies as a traditional subsonic jet.

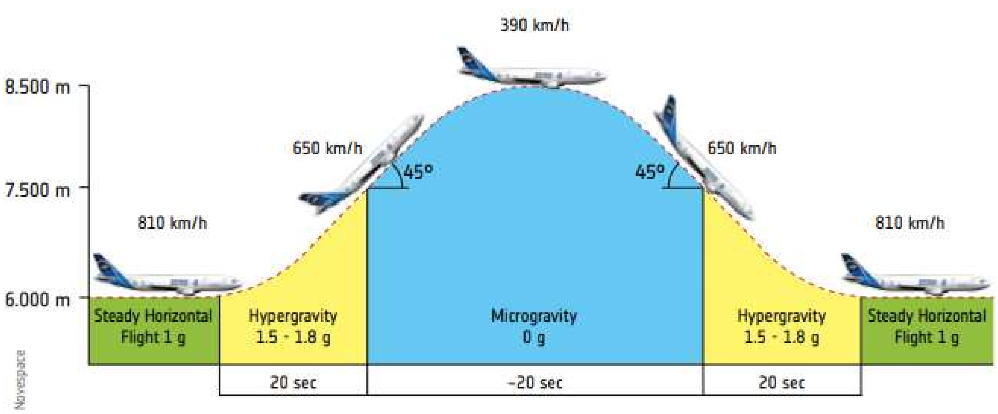


Figure 21: Suborbital parabolic flight, mission profile [23]

The main features of a suborbital parabolic mission are an altitude about 100 kilometers and maximum Mach of 4.

The Sub-Orbital flight is considered what can reach faster the commercialization. Now days, some private companies, as Virgin Galactic, have started to develop and to test some vehicles able to bring normal people in space. The suborbital parabolic aircrafts blend together aeronautical systems and technological solutions suitable for fling at high speed and high altitudes. One of the main challenge for these new type of industry is to be low-cost for increasing the number of costumers as much as possible. The use of reusable winged vehicle and a correct scheduling of the flights can reduce a lot the costs. Some studies, as the reference [22], show that a ticket for this flight could cost 200 thousand dollars.

Hypersonic point-to-point

The hypersonic point-to-point vehicle has a mission profile closer to the subsonic jet. In fact, they give the possibility to reach two antipodal cities without stops. In Figure 22, it is possible to see the mission profile of a hypersonic point-to-point vehicle.

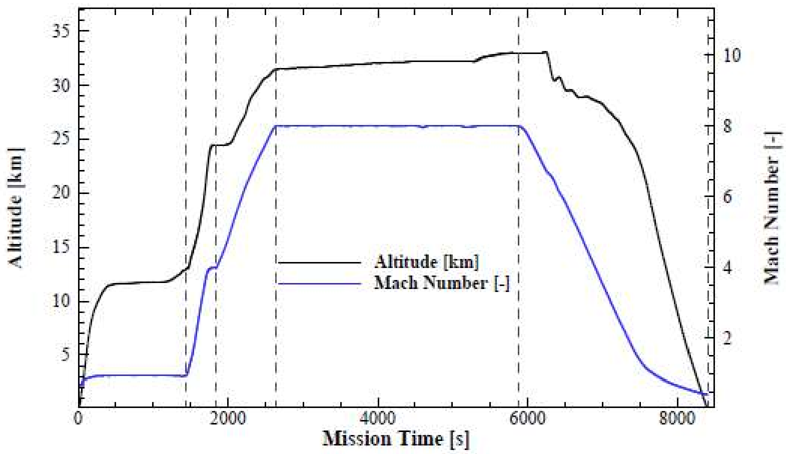


Figure 22: Mission profile of hypersonic point-to-point vehicle [24].

In the mission profile it is possible to identify three main phases: the climb to the cruise altitude, the cruise and the landing. The climb to the cruise altitude happens in steps, because the engines requires specific flight conditions to change the operative modes and for avoiding the sonic boom over populated areas. The cruise altitude is about 30 kilometers. The last part of the fly has the engines at minimum level of thrusts. The hypersonic point-to-point aircraft have a cruise Mach between 5 to 25.

The hypersonic point-to- point aircraft can be used for the passenger’s transport or as technological demonstrators for the access to space with reusable vehicle.

Today there is not hypersonic business jet. The route for the development of transportation point-to point without using “space-device” (as rocket engine) is at the beginning. It could give a great return, both under an economic aspect, and under the technological one. All the enterprises that work in the aerospace industries are sure of the long-term potential of intercontinental rapid flights. It is very challenging but different projects from privates or public agencies are in a development phase. One example is the LAPCAT project of ESA, that aims to design a hypersonic vehicle point to point with one stage and completely reusable. It should able to reach antipodal cities in few hours flying with a cruise Mach greater than five using airbreathing engines.

3.3 Evolution of hypersonic aircraft

The necessity to go faster than the others starts between the World War I and the World War II.

Doctor Eugen Sänger, an aerospace engineer of the university of Vienna, designs a winged vehicle able to do a parabolic flight to arrive anywhere in the planet in few hours. This vehicle is the Silbervogel, a sub-orbital rocket propelled by liquid-propellant.

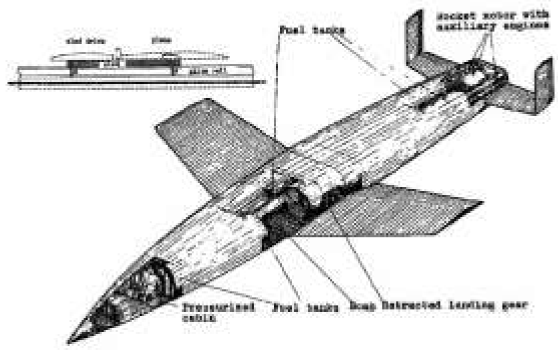


Figure 23: Image of the Silbervogel from the 1952 translated edition of Eugen Sänger and Irene Bredt's 1944 A Rocket Drive for Long Range Bombers [25].

It used liquid fueled rockets to reach the atmosphere and then it glided, with a parabolic flight, to the destination to bomb. It was the first intercontinental spaceplane, that could fly with hypersonic speed. It was called by its designer "Antipodal Bomber" and it could be a great weapon. It would be lunched by a sled. It would have a horizontal take-off. The Germany does not consider the Sänger project initially, because other projects of rockets had been developing in the same years (as the A-4, TH V-2 rocket, that flew above Mach 5). The Silbervogel development had been interrupted.

The U.S. Air Force started to study hypersonic vehicle after the Second World War at the same time of the start of the "space race". The USAF has tested hypersonic devices as intercontinental ballistic missiles, reentry and launch vehicles since the sixties. The United States had started the studies about hypersonic aerodynamic for both ballistic and lifting vehicles during the fifties. They built also facilities for texts, as hypersonic wind tunnels. In this period, the construction and the testing of "X-series" vehicles were initiated. It was an American program that aimed to develop a vehicle able to reach hypersonic speed. It lasted few decades developing various prototypes of aircrafts. At the beginning, there were some problems for transonic and hypersonic flight. The first airplane able to reach Mach 6.7 was the North American X-15. It was a rocket-powered trans-atmospheric aircraft. Three of this aircrafts model were built. the X-15 was fundamental in the hypersonic studies, because it was the first to test the high thermal load of the hypersonic flight. It shown how it was hard to overcome the aerodynamic effects with the technologies available at that time. The temperature reached was about 650°C and the fastest flight was with a cruise Mach 6.7. It was a manned vehicle and its pilots are considered as astronauts for the type of flight and altitudes. The performances reached by the X-15 were overtaken only by the Space Shuttle.

Figure 24: North America X-15 [26]

In the 1957 started the development Dyna-Soar (that stands for Dynamic-Soaring), a hypersonic boost-glide vehicle. This was a multiphase program that aimed to design a spaceplane able to bomb, to do aerial reconnaissance, satellite maintenance and inceptor and space rescue. One of the causes that closed the program in 1963 was the great confusion around the mission and the role of this type of vehicle. it was a manned vehicle. The Dyna-Soar project was more advanced than that period. This was another reason for delating the program, even if the construction had begun.

After that there was the Aerospace plan program, that was less supported than Dyna-Soar. It aimed to develop a single stage to orbit vehicle and later a two stage to orbit vehicle with a complex liquid propulsion system.

Subsequently those programs, the researches came back to design not complex system but demonstrators for testing the hypersonic flight conditions. The vehicles X-24A and X-24B were not hypersonic aircraft but they showed how the lifting-body configuration would be a feasible idea for the future high-speed airplanes. The X24A and the x24B could be used both as hypersonic cruise aircrafts and as reentry vehicles. In the same period, the Space Shuttle program needed more financings and the research in the hypersonic field went more slowly. At the same time, the Soviet Union were developing lifting bodies aircraft, for testing the low-speed landing and handling qualities.

The interest for the hypersonic started again in the 80s. In the USA, the aircraft X-30 was developed. It was a single stage to orbit with a horizontal take-off. In Europe, Hermes vehicle was designed by France. United Kingdom and Germany studies for a SSTO reusable spacecraft and a hypersonic airbreathing vehicle joined with a small rocket spaceplane or with a satellite insertion vehicle respectively.

From the first demonstrators and prototypes of the hypersonic flight story there was a big step forward under the aspects of technologies, material, design and mission requirements. The construction of X-Models aircraft is still running today. The USAF joins with other partners, as NASA or Boeing, to build aircraft for evaluating hypersonic technology. In the 2013, the X-51 Waverider, a scramjet demonstrator aircraft, reached Mach 5 and flew at this speed for 143 seconds. This performance has been the record of hypersonic flight with airbreathing engines. It has shown that the technologies are reaching the right level of maturity for a hypersonic fly.

The need for high speed arrived in the civilian aviation with the development of the Concorde in 1976. It was not a Hypersonic aircraft, because it flighted at Mach 2. The Concorde have fling for 27 years. It was retired after the terrible accident happened in 2000 at Paris airport after a take-off. Another cause for stopping this aircraft is the decision of Airbus not to do the maintenance again. This aircraft had some problems under the point of view of the environmental impact and of noise. It has been the possibility to civil aviation to flight faster than the traditional jets.

As said before, the hypersonic jet transportation is at the beginning. The performances required are completely different from the Concorde or the X-Planes. They were the first researches and projects in the hypersonic field. With their test, it is possible to develop new programs, that will bring great results in the aviation and will open new markets.

3.4 Reference aircrafts

This work aims at evaluating Direct Operating Costs of the LAPCAT A2, one of the configuration investigated in the LAPCAT project. This study was carried out by the European Space Agency and it aimed at developing a hypersonic point-to-point vehicle able to reach Mach 5 with airbreathing engines.

Before starting with the description of the LAPCAT project, other reference aircrafts are here described. Depending on their specific similarities with respect to the LAPCAT A2 vehicle and/or mission, they have been considered as reference for in the cost estimation procedure.

North American XB-70 Valkyrie

The North American XB-70 Valkyrie was a high-speed manned strategic bomber. It flew at Mach 3 with an operating altitude of 70000 feet (21000 m). It was developed for the United States Air Force Strategic Air Command by NASA. It flew for the first time in 1964.

Its structure was fundamental to have its performances. Indeed, its wings could bend their tips to entrap the shock waves, born by reaching supersonic speed. This gave the possibility to the airplane to ride its own shock wave and to have greater aerodynamic performances due to the generation of additional lift.

It was propelled by six jet engines built under the fuselage and the delta wing. Its structure is made by stainless steel honeycomb and titanium.

For the landing it used the parachute for increasing the drag and for reduce the landing length.

Even if only few flights were made by the prototypes, the XB-70 gave the possibility to evaluate the problems due to a supersonic speed and to the vehicles configuration. Those were aircraft noises, operational problems, design of the control system, differences between the data predicted in the wind tunnel tests compared to the flight data and turbulence.

One of the prototypes had a terrible accident in June 1966 and the crew members died.

This vehicle has been chosen as references for the peculiarity of it structures and for the materials of the structure.

Figure 25: North American XB-70 Valkyrie [27].

North American Aviation X-15

The X-15 was the most successful research program in the field of high speed flight. The structures, the propulsion system and the control techniques were developed purposely to study the hypersonic flight regime. Another aspect was to analyze the possibility to flight outside the atmosphere. When it flew in the atmosphere, it needed conventional aerodynamic control surface. When the flight was in higher altitude, the vehicle used special thruster reaction control rockets. The X-15 was launched from a B-52, because of the large fuel consumption of the rocket engine.

The first flight was in the June 1959. The fastest flight was at Mach 6.06. The highest altitude reached was 354200 feet. The pilots were qualified as astronauts for the flight altitude. One of the twelve pilots of X-15 was Neil Armstrong.

The X-15 was rocket propelled and it was the first manned winged vehicle that reach hypersonic speed. It withstood to a temperature of 650°C. For this reason, it was built in a special high-strength nickel alloy named Inconel X 750. The pilots were protected from the heat by full-pression suits.

The X-15 project was a great possibility to do research in a lot of fields as hypersonic aerodynamics, winged reentry vehicle from space, aerodynamic heating, heat transfer and life-support equipment.

Some records reached by the X-15 and this program are still valid, as the fastest flight.

X24

It was a program directed by NASA Flight Research Center to develop a group of lifting body aircrafts. It started in 1963 and it finished in 1975.

The lifting body aircrafts were used to train the pilots to maneuver correctly and safely vehicles designed to come back to the Earth after a space mission and to land at defined site as a common airplane. These airplanes do not reach hypersonic speed but they were useful to study the lifting bodies aerodynamic. The training of the pilots was also another relevant aspect. The X-24 program helped also for the first studies about the Space Shuttle landing.

The two models developed are shown in the following figures.

Figure 27: X-24A [26].

Figure 26: X-24B [67].

X-30

The X-30 was the name of a single-stage-to-orbit with horizontal take-off and landing aircraft. It was built in the program NASP, National Aero-Space Plane, directed by DIARPA, Defense Advanced Research Projects Agency, NASA and USAF between 1982 and 1985.

According to the initial idea this vehicle had flew at Mach 25 using airbreathing engines as primary propulsion. In this program, some studies were done about the high temperature materials: carbon-carbon materials, lightweight titanium and beryllium alloys, and high strength, corrosion-resistant titanium-alloy composites.

The program involved the major aerospace enterprises in the Unites States but it was stopped in the 1994 for the high cost and the technical difficulties. Only a 1/3- scale concept demonstrator was built. This program was useful for the future research in the hypersonic filed, in particular for its airbreathing propulsion.

Figure 28: X-30 [26].

X-33

The X-33 is a project made by NASA and an enterprises' team lead by Lockheed Martin. It would be a suborbital demonstrator able to flight at Mach 15 (that was reduced at Mach 12 after further studies).

It was a half-scale prototype of the VentureStar, a reusable launch vehicle. It had vertical take-off and horizontal landing. It was developed for testing the aerospike engine, the metallic thermal protection system and the composite liquid tanks. It would test the difficulties of a severe launch site environment. It was an autonomously piloted vehicle.

The problem with this project arrived soon. There were some failures in the fuel thanks and this increased the overall cost. Those aspects stopped the program. The most interesting features of this vehicles was the all-body configuration.

Figure 29:X-33 [28].

X-38

The X-38 was a demonstrator of crew rescue vehicles for the International Space Station. It was designed by NASA and the program was stopped in 2002.

It had a lifting body design and it glided to the ground opening steerable parafoil parachutes for landing. The development cost had been significantly reduced using off-the-shell equipment and available technologies (the final cost was a quarter of the one originally estimated).

One of the most interesting aspect of the program is the materials used: it was a shell made of composite materials such as fiberglass and graphite epoxy and strengthened with steel and aluminum. The pressurized chamber for the crew was made in aluminum. The thermal protection system covered the crew compartment and the fuselage. It was made by similar material of the Space Shuttle, but more durable: carbon and metallic-silica tiles for the hottest parts and flexible blanket-like material for the coldest ones.

Figure 30: X-38 [26].

Skylon

The Skylon is a project of REL, British company Reaction Engines Limited. It is a single-stage-to orbit vehicles propelled by SABRE engine, a combined air-breathing rocket propulsion system. It is designed to reach the Low Earth Orbit. It uses liquid hydrogen and it is able to reach Mach 5.4 at 26 kilometers altitude using only the oxygen in the atmosphere. After this phase, it changes fuel using liquid hydrogen to go in orbit.

It has horizontal take-off and landing. In the last phase of flight, when the thermal load is highest, it is protected by a ceramic composite skin. It is a reusable vehicle and the maintenance required is minimal compared to other spaceplanes.

The test phases of the major technologies were usefully concluded in 2012. The first unmanned test flight is planned to be in 2025.

The payload is estimated to be major than the one of the current supply vehicles. This reduces the cost per kilogram for carrying payload to Low Earth Orbit.

The Life Cycle Program cost of the Skylon is estimated to be 12 billion of dollars. The project has been initially financed by privates' enterprise with a contribution of the European Space Agency.

Figure 31: Skylon [29].

Saenger

The Saenger was a concept design of two-stage-to-orbit vehicle designed by West German. Its name came from Eugene Sänger, the pioneer of hypersonic field and the designer of Silbervogel. This project had the support of German Aerospace Center, DLR. It was a part of a national hypersonic study.

The first development started during the 1960s. It could be used both as hypersonic passenger airplane and as two-stage lunch vehicle to bring different payload to orbit, including astronauts. The interest around the Saenger had increased, because it could be a reusable launch vehicle. The project was stopped in 1995 because the costs are much higher than they were anticipated and the results are poorer than the ones of the expandable lunch vehicle already operative, the Ariane 5.

SpaceLiner

The SpaceLiner is a concept for the design of suborbital hypersonic winged vehicle. It is developed by the German Aerospace Center (DLR). This aims to start a sustainable low-cost space transportation to orbit and to make the flight between two opposite parts of the world faster. The project started in the 2005 and now the Phase A of Conceptual design is finished with the sizing of the major subcomponents in nominal and off-nominal conditions.

The concept is a two-stage-to orbit vehicle with a vertical take-off and a horizontal landing. A part of the vehicle is the large unmanned booster. Another one is a manned passenger stage designed for 50 passengers and 2 crew members. The first part of the flight is made using nine rockets fueled with liquid oxygen LOX and liquid hydrogen LH2. When the fuel finishes, the booster is cut-off and the passenger compartment can glide to reach antipodal destination with a parabolic flight. The SpaceLiner can fly from Brussels to Sidney in 90 minutes with a cruise Mach of 20 and a maximum altitude of 80 kilometers. The separation of the stages happens at Mach 12.5. All parts of the vehicle will be reusable. The orbiter tries all regimes of flight: from hypersonic to transonic during the cruise and subsonic during the landing. An escape system is designed to eject the payload compartment in case of emergency.

Figure 32: SpaceLiner [30].

3.5 The LAPCAT project

The LAPCAT project started in the 2005 under the guide of ESA-ESTEC, that coordinated twelve partners between industries, universities and research centers.

LAPCAT (Long-Term Advanced Propulsion Concepts and Technologies) main goal was to design a propulsion concepts for sustained hypersonic flight. The idea is to reduce the time of flight and to reach a city at the antipode of the world in few hours. This type of flight regimes required a cruise Mach higher than 4-5, implying also an increment in flight altitude.

The traditional turbojets cannot sustain these speeds and thermal loads. They are not able to operate at such altitudes. They can be replaced by different types of propulsion systems. In particular, apart from rocket motors, advanced airbreathing engines, that use different combined cycles as TBCC and RBCC, Turbine Based Cycle and Rocket Based Cycle, can be exploited. Due to the relevant coupling of aerothermodynamic issues of the inlet of the propulsion system with those of the entire vehicle, the vehicle design should be carried out in combination with the engine design. In particular, it is possible to define this project as “technology pushed”. In fact, the main technology is the airbreathing engines and all the other decision about design and systems is linked to this one.

The LAPCAT project aims to give the basis for the introduction of advanced propulsion concepts. It is started in 2005 and consisting in different phases. The firs one lasts 36 months and aims to define requirements and the operational conditions on system level, to test different aspects of the hypersonic fly and to validate a physical model integrated into numerical simulation tools. It aims to evaluate the most critical aspects of the utilization of advanced technologies for the passenger’s transport, using tool developed ad hoc. According to the reference [31], the technological and scientific goals are:

- To evaluated two advanced airbreathing concepts
  To reduce the time of flight a Turbine Based Cycle and a Rocket based Cycle are considered. The project should analyze completely the two different engine concepts, considering a reference mission and a specific vehicle design
- To analyze the critical technologies for each cycle.
  It should be evaluated their functioning in each possible flight condition.
- To do specific combustion experiments
  These experiments are necessary to evaluate the performances of each cycle. They need also to evaluate the differences between different types of fuel, considering also the environmental impact. It is possible to develop a simulation tool with the data collected.
- To model and validate a numerical simulation tool for combustion physics
- To do aerodynamic experiments
  The aerodynamic of the hypersonic range has different features than the subsonic or the sonic one. Some tests are necessary both to validate the theoretical data both to design each component properly. The data collected give the possibility to create a database, that can be used for a design tool.
- To evaluate and validate a computational fluid dynamic tool.
  It is necessary to simulate the difficult flight conditions of a hypersonic flight, in particular the turbulence and the transition of the fluid.
- To design, to develop and to test specific hardware components.

The LAPCAT project should define the requirements and operational conditions on system level. It should carry out specific and accurate experiments in different fields, as aerodynamic or propulsive. The collected data give the possibility to create more precise models and numerical simulation tools.

During the project, different vehicle configurations have been designed, depending on the propulsion system architecture. One of them, the LAPCAT A2, has been chosen as the reference vehicle for the direct operating cost evaluation, because some cost estimations for the vehicle and for the main components are done.

Before analyzing the reference vehicle, it is interesting to describe the LAPCAR MR2. It is another vehicle configuration studied by the LAPCAT project. In some ways, it can be considered an evolution of the LAPCAT A2. It has not been chosen as reference vehicle because there are not any economic data or evaluations.

One of the goals of the LAPCAT MR2 is the possibility to reach Mach 8 during the cruise phase. Its configuration is shown by Figure 33. It is the evolution of another vehicle concept, the LAPCAT MR1 (Figure 34)

Figure 33: LAPCAT MR2 [32].

Figure 34: LAPCAT MR1 [33].

Under the aspect of the technologies, two elements are very important for this vehicle:

- Propulsion system
- Thermal Energy Management System.

The engines of the LAPACT MR2 are ATRs (Air Turbo Ramjet) for speed below Mach 4.5 and DMR (Dual Mode Ramjet) for flying between Mach 4.5 and Mach 8. This choice is different choice than the LAPCAT A2, that use only a type of engine that can be compared to a turbojet or a ramjet according to the different flight conditions. The presence of ATR and DMR is very importation under a configurational point of view. The two types of engine share the intakes, that should be long enough for having the right fluid compression in the hypersonic flight. This is a limit for the vehicle that should be sufficiently big to contain the intake.

The second significant technological aspect is the TEMS, the Thermal Energy Management System. It permits to cool the passengers compartment taking advantage of the physical properties of the fuel. The fuel is the liquid hydrogen, as in the case of the LAPCAT A2. LH2 is cryogenic and it is possible to use the vapor of boil-off to cooling all the critical parts of the structure. The passengers' area is surrounded by tubes where the vapor of LH2 can flow reducing the high temperature due to the thermal load of hypersonic speed. The vapor of LH2 goes again in the tanks, after having refrigerate this part of the vehicle.

The particular configuration of the LAPCAT MR2 comes from the need to integrate the high-performance propulsion within an aerodynamic efficient waverider design. Sufficient volume for tankage, payload and other system should be guaranteed. In Figure 35, there is the configuration of the LAPCAT MR1.

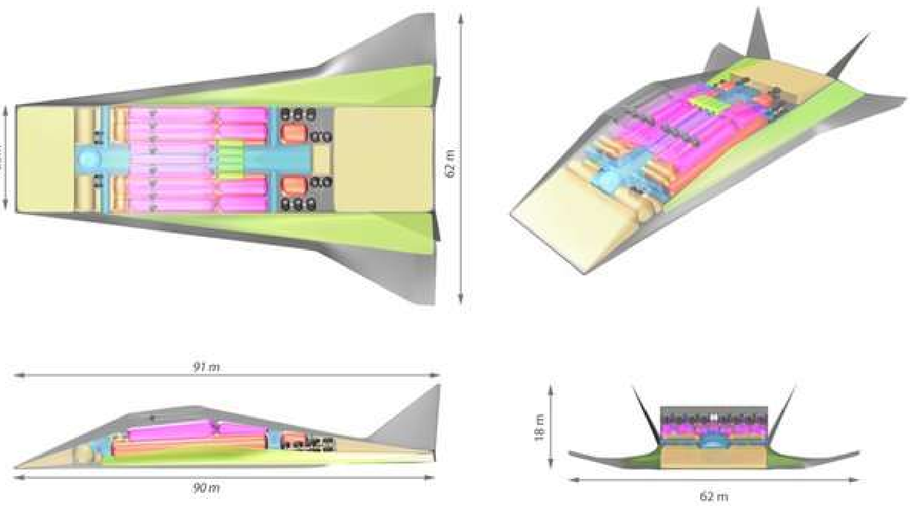


Figure 35: LAPCAT MR1 Configuration [34].

In Figure 36, it is shown the mass brake-down of the LAPCAT MR2. It is interesting the fact of the weight of fuel is about the half of the total take-off weight. The same happens for the LAPCAT A2. In the case of the reference vehicle, the payload weight is the 30000 kg.

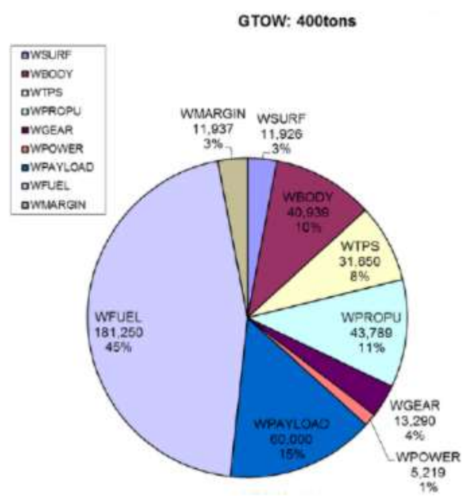


Figure 36: GTOW Mass break-down of LAPCAT MR2 [35].

Also for the LPACT MR2, the reference mission is a flight between Brussels to Sydney. The conventional routes cannot be used, for the problems due to the hypersonic speed, as the “sonic-boom”. The LAPCAT MR2 takes 2:55 hours to reach the Australia from the Europe. In this case the cruise speed is MACH 8 and the cruise altitude is about 30-35 kilometers.

As said before the LAPCAT project aims to analyze the possible concepts of engine to reach hypersonic speed. It studies their integration in a complete vehicle with a reference mission. The LAPCAT A2 has a Mach 5 cruise. The gross take-off weight is 400 tons and it can carry up to 300 passengers between two antipodal locations. The vehicle has a slender fuselage with a small delta wing closed to the middle length of the fuselage, where four nacelles are placed. To have good handling qualities both at low speed and at hypersonic one, the airplane is controlled by active foreplanes in pitch, aileron in roll and all moving fin in yaw. This configuration gives the possibility to have a better aerodynamic efficiency both in cruise and in the low speed phases of the mission, as the take-off and landing.

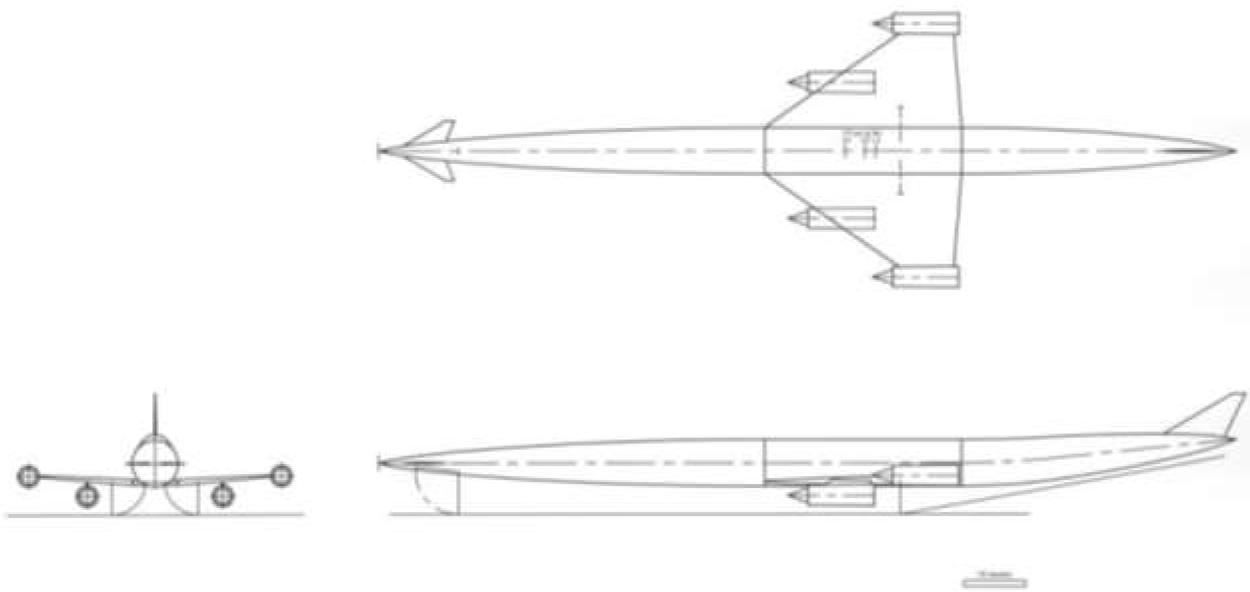


Figure 37: LAPCAT A2 configuration [36].

Some choices for the wing configuration are like the Concorde features. For instance, the leading-edge sweep angle is 55 degrees, because it is the minimum value to generate separated vortex at high angle of attack. Other characteristics, as the value of thickness to chord ratio, are like the ones of other hypersonic vehicles. The area of the wing is evaluated considering the take-off weight and the lift coefficient at the first phase of flight. It is 900 square meters. The fuselage is 139 meters long. Its diameter is 7.50 meters. These values depend on a trade-off between a little increase of the drag and a saving in the mass. In Figure 38, it is possible to see the LAPCAT A2 vehicle. In Figure 39, there is a comparison of this vehicle with an airbus A380 to understand better the dimension of the aircraft.

Figure 38:LAPCAT A2 vehicle [36].

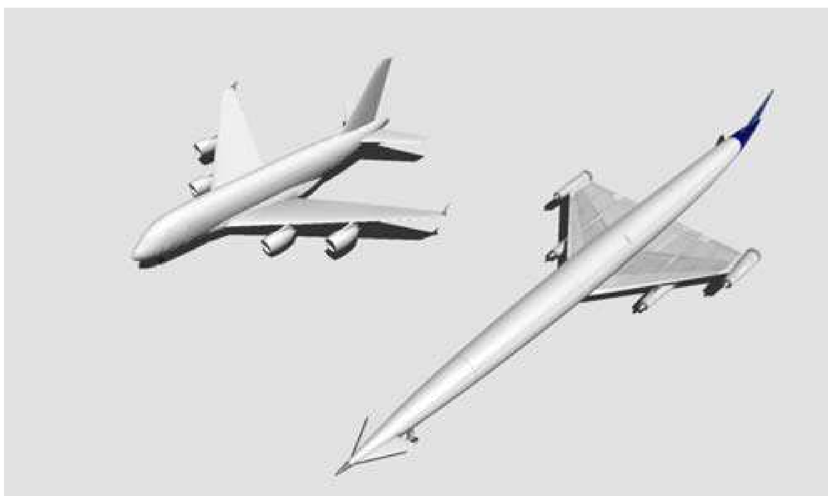


Figure 39: Comparison between the LAPCT A2 and an A380 [37].

The crew and the passenger compartments are located at the middle of the fuselage close to the center of gravity. It is 32 meters long.

The fuel is liquid hydrogen because it is the only propellant able to achieve antipodal flight for its high specific energy content. Unfortunately, it is cryogenic with a very low boiling point and it has low density and inherently low volume. The tanks for the storage should be heavier and with a bigger volume than a subsonic jet. For this reason, it is not possible to use the wings volume as the conventional aircrafts because it is too small. The LH2 tanks occupied the remining space of the fuselage. There are two large pressurized tanks at the both sides of the passengers' compartment. They have a circular cross section which minimizes insulation and pressure vessel mass.

The four engines are positioned in four axisymmetric nacelles into the wing. The number is chosen for redundancy. Two engines are on the wing's tip, the others are closer to the fuselage at the leading edge. For increasing the safety, the nacelles are separated. In this way, if there is a failure of one engine, the risk of damage for the others is lower. Placing the engines on the wing, gives the possibility to control better the stability of the vehicle. According to some detailed studies [36], the large yawing moment due to the engines on the wing is well controlled by the movement of the fin. The force generated by the fin has a long arm and the moment gives the possibility to control properly the vehicle. Other possible positions for the engines are on the fuselage or at the rear of the fuselage. In the first case, there are problems of acoustic fatigue on the fuselage skin and a large diverter boundary layer. In the second configuration, the center of gravity would be pushed too back.

Probably the most interesting feature of this project is the engines. The LAPCAT A2 has four precooled engines called Scimitar. They are based on the Reaction Engine of SABRE spaceplane and are propelled by liquid hydrogen. This type of engines has good performances both in hypersonic and in subsonic flight. The Scimitar permits to use the airplane over inhabited regions and operate in the conventional airports, avoiding the hypersonic problems as the noise and the limitation impose to sonic flights. The Concorde had some problems with the noise and sonic boom. Those limited its operations. This will not happen to the LAPCAT A2. As said in the refence [36], it is fundamental the engine configuration to achieve the performances of hypersonic flight. The Scimitar has a high bypass fan integrated into the bypass duct that surrounds the engine core. It is necessary that the duct matches perfectly the intake air capture flow. The bypass fan is kept in movement by a turbine using flow diverted from engine nozzle. The flow reduces its power, it passes into the bypass and it is mixed with the bypass flow. Two important elements of the engine are a lightweight heat exchanger and a contra-rotating turbine. The air precooler is positioned immediately after the intake and it is made by a matrix tubular material over a small diameter tube bank. In the tube, there is helium that should be maintained at 1000 K for having the best engine performances. To heat the helium is used a preburner. At high temperatures, there are some straight problems with the metallic materials. It is analyzed to use Si-C material to maximize the performances and avoiding failures. Some tests should be done on the stator-less contra-rotating turbine. The engine is in a preliminary design phase and it is impossible to do aerodynamic tests on the real component and to simulate the operative conditions. A mathematical model is created to simulate the performances of the component. The test program started in the 2008 and it shows how an ultra-compact turbine can be used for hypersonic engines application. The first analysis demonstrated that the scimitar engine is efficient both in hypersonic and in subsonic conditions and it respects the regulations for the normal airport.

Another critical aspect for the hypersonic engines is the environmental impacts. especially, it is important to control the NOx production that damage severally the Ozone. The present configuration of the Scimitar is not environmental friendly, because there is a significant production of NOx. Some changes to improve the emissions can reduce the performances, but they are being studied for avoiding environmental problems and limitations.

In Figure *40*, it is possible to see the configuration of the Scimitar.

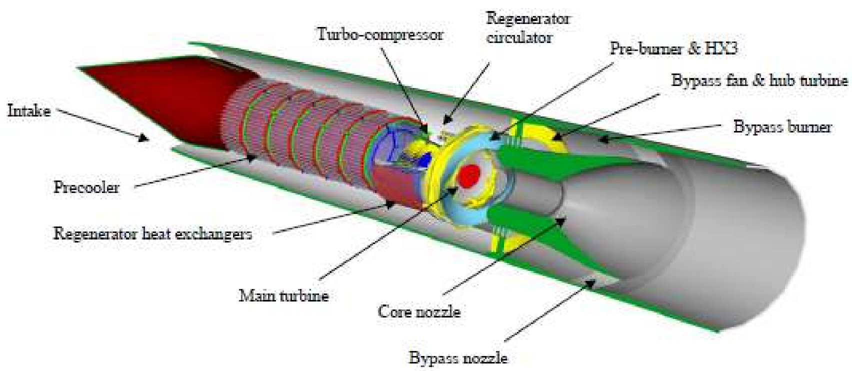


Figure 40: Section through Scimitar Installation [38].

In Table *4*, there are the engine performances at different speed considering the various mission phases.

Altitude m	Mach	Equiv. Ratio	Thrust N	Airflow kg/S	Air-fuel ratio	Flight Phase
5.3	0.329	0.8	372254	519.9	42.87	Runway acceleration with reheat
1230	0.408	0.407	248134	477	84.28	Subsonic acceleration with reheat
16577	2.5	0.7	272771	284.2 (intake spilling)	48.98	Engine mode change subsonic phase
16577	2.5 (B-mode)	0.7	313105	349.5 (full capture)	48.98	Engine mode changes hypersonic phase
5900	0.9 (P-mode)	0.0749	81873	390.4	458	Subsonic cruise
25400	5	0.8	168348	173.6	42.87	Hypersonic cruise

Table 4: Scimitar engine performances [38]

In the case of hypersonic vehicle, it should be considered that the traditional routes cannot be used and they should be changed. There are the problems of the “sonic boom” and of the ground overpressure produced by a supersonic/hypersonic flight. The maximum overpressure tolerable for light over populated regions is 50 Pa. This level is too low for hypersonic aircrafts, in fact the Concorde had an overpressure of 93 Pa. The first studies about the LAPCAT A2 show an overpressure of 85 Pa under the ground track and about 70 Pa at the middle of cruise. The supersonic/hypersonic routes should be over regions with a lower density of population, as the Poles or the oceans. Another possibility is to flight over the desert regions of the Africa or the Australia. In the preliminary studies about the operating scenario, the last option is not considered, because the worst condition and the longest range have been simulated. The reference mission is a flight between Brussels to Sydney. It is about 17000 kilometers. The LAPCAT A2 takes about 4 hours to reach them with a cruise speed of Mach 5 at an altitude of 25 kilometers. This route is considered as the baseline mission because many hours are required for reaching those antipodal cities with a traditional aircraft. So, the introduction of a hypersonic aircraft could bring great advantages. In the Figure *41*, it possible to see the mission path on the map.

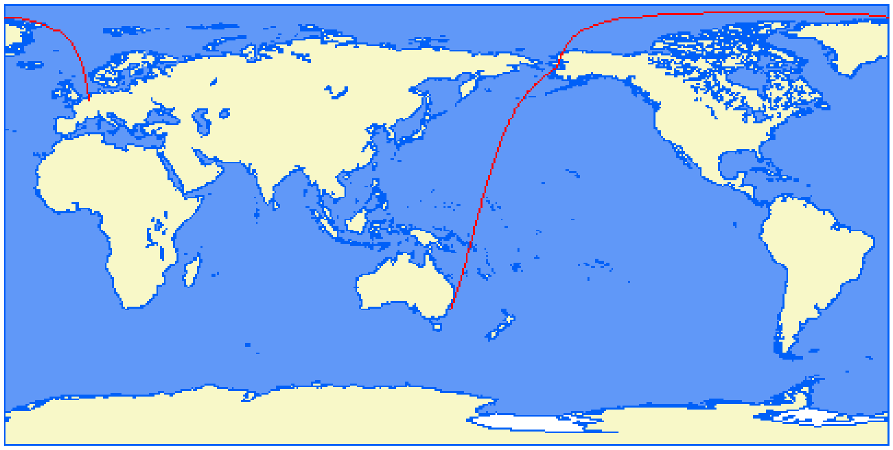


Figure 41: Brussels to Sydney via Bering Strait (18728 km) [36].

Other interesting routes are show in the Table 5, where the times of flight of a subsonic jet and of the LAPCAT A2 are compared.

Route	Subsonic aircraft	Mach 5 aircraft
Brussels – Sydney	22.25 hr	3.8 hr
Brussels – Los Angeles	10.0 hr	2.5 hr
Brussel – Tokyo	10.75 hr	2.5 hr
Brussels – New York	7.5 hr	1.6 hr
Brussels – Beijing	8.9 hr	4.9 hr
Brussels – Delhi	7.2 hr	5.3 hr
Paris – Kourou	7.9 hr	1.7 hr
Los Angeles – Tokyo	9.75 hr	2.0 hr
Los Angeles – Sydney	13.4 hr	2.6 hr
Los Angeles – Singapore	15.7 hr	3.0 hr
Los Angeles - Delhi	143 hr	7.5 hr

Table 5: Approximate flight time for different routes.

It is interesting to see how great is the time saving for a route that lasts many hours as the Brussels-Sidney. The time of flight of LAPCAT A2 is evaluated thanks to a specific program, ASTOS, that simulates the trajectory. Some assumptions are made for analyzing the reference mission:

- The flight path is over the Bering Straits to no overfly densely populated areas
- Not wind (jet stream) effects are considered
- It is not considered airport straight approach
- It is considered nominal ascent and descent times and distances

A detailed trajectory simulation shows that the time necessary to flight from Brussels to Sydney is 4.6 hours. In this case, the time of ascent and descent increases because the trajectory is better simulated. Two hours of stop for the refueling are also considered in the case of subsonic aircraft mission.

In the Figure 42, Figure 43 and Figure 44, it is possible to see the flight path of some missions present in the Table 5. Differently from the Concorde, the LAPCAT A2 has a great range, that gives it the possibility to service many the routes. The Scimitar engine is good in subsonic and in hypersonic flight. The vehicle can fly over populated areas without any problems. This is a great advantage for the LAPCAT A2, that can enlarge its market.

Figure 42: Brussels-Beijing via Nome and Tokyo (14,100 km) [36].

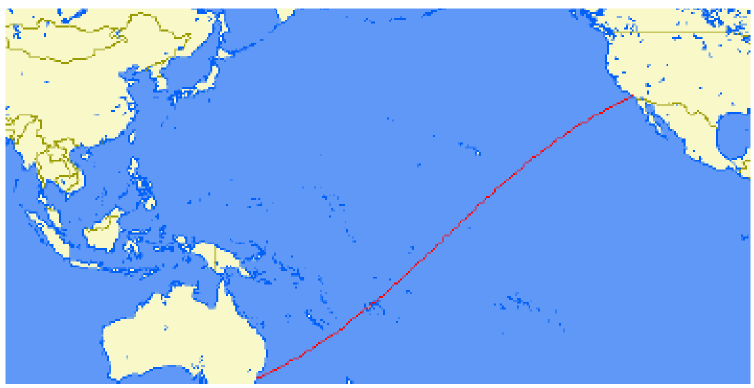


Figure 43: Los Angeles-Sydney (12,071 km) [36].

Figure 44: Los Angeles-Delhi via Singapore (18,256 km) [36].

As said before, the LAPCAT A2 is chosen as reference vehicles because a preliminary economic study is made.

The 2023 could be a feasible data for the entrance in service of this vehicle. Before building the aircraft, there are a concept validation phase, a technology demonstration phase and a system development phase. The cost estimation was made in the 2006. It was predicted that the total development cost is 22601 $M€_{2006}$. 8147 $M€_{2006}$ is the development cost of the engines and 14545 $M€_{2006}$ is the cost for the development of the overall vehicle. Initially, it was considered the production of 100 aircrafts and a learning factor of 85%. So, the average price sale is about 639 $M€_{2006}$ for each vehicle, including full development cost recovery. The estimated operating cost per year is 553.8 $M€_{2006}$. In the case of hypersonic aircrafts, the major cost item is the fuel. In fact, the operating costs linked to LH2 is 83% of the total DOCs. This cost of fuel depends also on the productive method. It has assumed that liquid hydrogen is produced by water's electrolysis. The use of other productive methodology, as steam reforming of hydrocarbons, could reduce fuel's cost. For the first estimations, it has decided to consider two flights per day with the 90% of availability and the 75% of load factor. With those data, about 148000 passengers can be carried each year. The ticket price for the route Brussels – Sydney should be about 3940 € in the 2006. It is more competitive than a business class ticket (about 4060 €) or a first-class ticket (about 5075 €).

4. NASA Direct Operating Costs' equations

In the first chapter of the Thesis, some methods for the cost evaluation are briefly summarized. Now, it is analyzed the NASA methodology for hypersonic transport technology planning [16]. It allows to evaluate the direct operating costs for a hypersonic point-to-point vehicle. It is based on a set of cost estimation relationships developed by ATA [1]. The NASA method has been chosen for the evaluation of the direct operating costs of the LAPCAT A2, because it seems the more appropriate to a hypersonic vehicle. Indeed, it is the only one that permits the evaluation of the DOCs of hypersonic vehicle. Furthermore, the NASA modified ATA CERs evaluate the direct operating costs for a hypersonic point-to-point airplane that uses airbreathing engines. These features are the same of the reference vehicle.

Initially, there is a detailed description of the NASA methodology for hypersonic transport technology planning. The baseline used by NASA for the cost evaluation is presented. The technological drivers, i.e. the parameter of the equations directly link to the hypersonic features, are illustrated.

After that, there is the analysis of each of cost evaluation relationships present in the NASA modified ATA CERs. It also has an explanation of the terms and coefficients of each equation.

Subsequently, there is the analysis of some relevant terms. According to the NASA report [18], this operational constants and cost factors are relevant for the cost estimation. It is important to understand well what they mean for having a correct evaluation of the costs.

In the following section, there is the cost estimation made for the NASA baseline. There is also the comparison with a subsonic jet cost. It is interesting to see the differences between the cost items of estimations of the two types of vehicle.

At the end, there is an analysis of the most relevant aspect of the equations. In particular, it is underlined which factors can have a great influence on the DOCS of hypersonic vehicle. They should be considered for evaluating the technological impact on the direct operating costs and for developing a new set of equations.

4.1 Description of NASA modified ATA CERs

The goal of this thesis is to identify mathematical relationships to estimate the direct operating costs for a hypersonic airplane for civil transport. The reference vehicle is the LAPCAT A2. This airplane is a point-to-point aircraft that carries passengers with Mach 5 cruise speed.

The first step has been the study of the state-of-the-art for analyzing mathematical relationships available in literature for the DOC estimation of hypersonic aircraft.
After a research of the literature sources, it has been chosen the document [17] as reference. It is a NASA report where DOC equations are reported and they are applied to a case study of a hypersonic aircraft.

The objective of NASA's study is to develop a systematic procedure for estimating the impact of technological improvements of vehicle configuration on the direct operating costs. This is possible after the identification of a baseline of hypersonic cruise transport (HST). It can have different systems or mission configurations and the NASA method gives the possibility to evaluate the changing of costs with different technological improvement. It is important to know some high-level design data, that should be used in the second part of NASA's procedures, where the direct operating costs formulas are used for the baseline. The DOC equations are derived from Air Transport Association of America (ATA) convention, but some changes are brought to adapt them to hypersonic study. The DOC "Drivers" are identified in the formulas. They are some equation's elements directly linked to hypersonic technologies. They have a strong impact on direct operating costs. For instance, one of the drives is the lift-to-drag ratio. Another part of NASA's method is the analysis of the modifications of DOC drivers, when some technological parameters changes. Technological parameters are lower level terms then the Drivers. They are closer to hypersonic research. They are specified for each baseline. An example can be the aerodynamic coefficients. The last part of NASA's study is the analysis of the impact of technological improvement on the direct operating costs. This is possible modifying the technological parameters. The last part is the analysis of the results. It is possible to know the direct operating costs using the baseline's parameters in the formulas. Thanks to the using of NASA's DOC equation, it is possible to carry out economic and sensitivity analysis about which technological improvement are real useful to DOC savings. The Figure 45 shows the NASA's method that supports the technology planning.

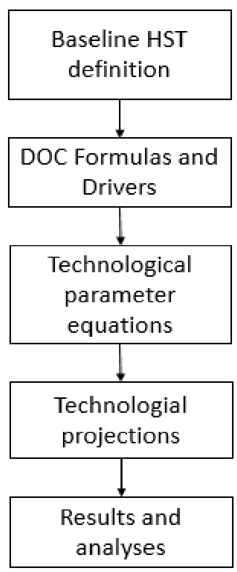


Figure 45: NASA Method [17].

The NASA equations can be applied to assess the cost estimations of hypersonic aircraft that uses air-breathing engine and has horizontal take-off and landing, like LAPCAT A2. The method can be applied to aircraft that flies with a Mach number from 5 to 12. The fuel type is not important, because the methodology is not strongly dependent from this variable. So, either hydrocarbon fuel or liquid hydrogen can be chosen. In *Table 6* there are the application limits of the NASA modified ATA CERs.

Variable category	Major alternatives accommodated
Payload	Cargo, passengers or combination
Cruise Mach no.	5 - 12
Fuel type	Liquid hydrogen, jet fuels, methane, etc.,
	and combinations
Structure	Actively cooled, uncooled, or combination
	Integral or non-integral fuel tanks
Aero configuration	Blended wing-body, all-body or conventional.
Propulsion	Separate turbojets and ramjets or integrated
	propulsion systems; supersonic or subsonic
	combustion, or dual-mode ramjets

Table 6: Baseline major features [17].

The NASA baseline used for the cost estimation is a cargo airplane with a cruise Mach number of six and with an operational range of 7400 km. The HST mission profile is in Figure 46. The altitude is ranged from 27600 m to 28800 m and the mission duration is about two hours. The aerodynamic performances are represented by the lift-to-drag ratio. It is 4.6. This is a more conservative value than the one obtained in the wind tunnel trial. The NASA method requires some operational characteristics. In particular, the baseline depreciable life is ten years. During the depreciable period, the utilization is about 30000 block hours and it has 13350 flight cycle.

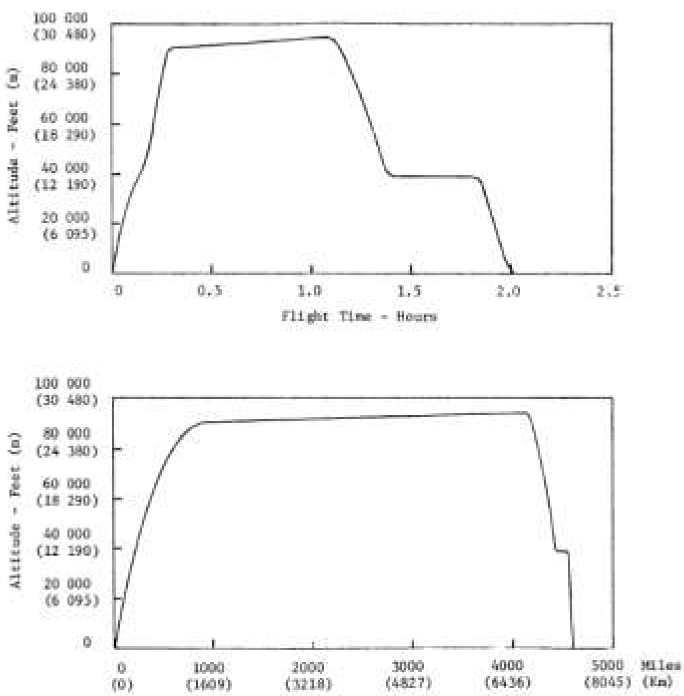


Figure 46: Mission profile of baseline [17].

The structure of the baseline is shown in the *Figure 47*

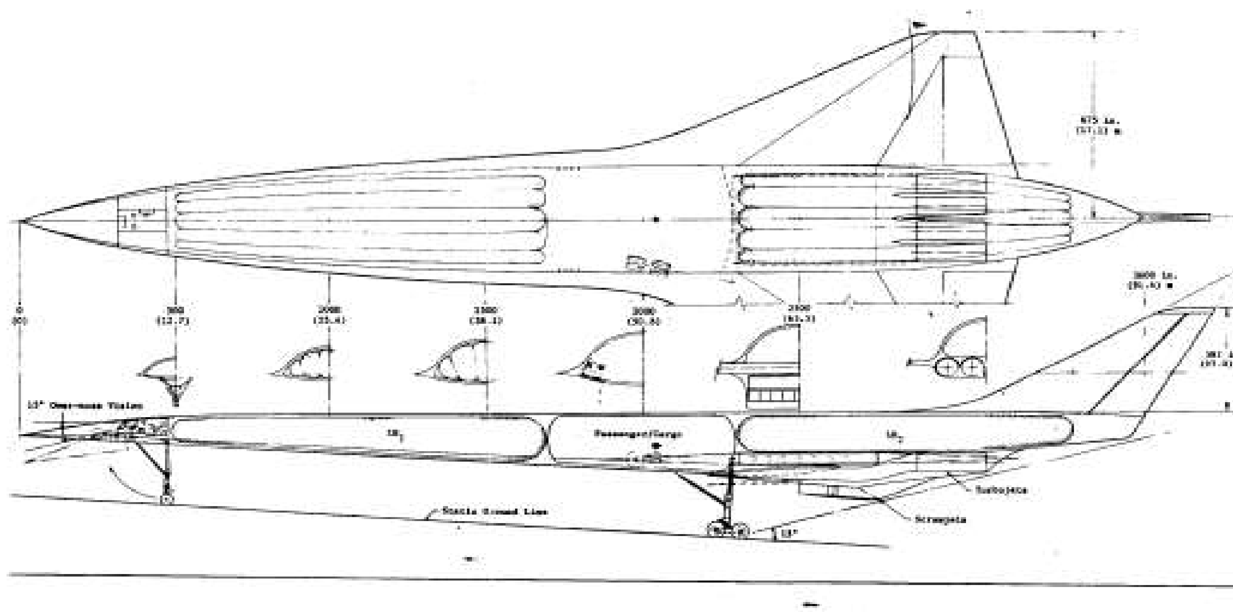


Figure 47: Baseline hypersonic transport [17].

The fuel is liquid hydrogen and the tanks are located in the forward and in the aft fuselage for weight and balance considerations. The payload space is in between the two tanks areas, closed to the center of gravity for balance control. The shape of fuselage guarantees a continuous pre-compression surface for the engines. The ramjet has dual mode combustion: a subsonic combustion when the airplane passes through transonic and supersonic speed, and a hypersonic one for the cruise phase at Mach 6. The turbojets are shout down at Mach 3 and they are used for the initial phase and for the loiter and landing. The material of the structure is aluminum alloy 7075-T6 convectively cooled using water-glycol as heat transport fluid.

A crucial step in the NASA method is the identification of the Driver Parameters to be inserted in the various formulations. They are directly linked to the new technologies and they are present in the DOC Formulas more or less clearly. They are:

$\frac{W_{AF}}{W_{GTO}}$	Airframe weight fraction which includes the following elements: • W_f/W_{GTO}: fuselage weight fraction • W_w/W_{GTO}: wing weight fraction • W_e/W_{GTO}: horizontal and ver%ical surfaces weight fraction • W_{tp}/W_{GTO}: thermal protection weight fraction • W_{ps}/W_{GTO}: propellant system weight fraction • W_{sys}/W_{GTO}: other airframe systems as landing gear, power, hydraulics, etc.
$\left(\frac{W}{T}\right)_{TJ}$	Turbojet propulsion specific weight
$\left(\frac{W_{RJ}}{Ac\ C_{TRJ}}\right)$	Ramjet sizing parameter
sfc	Cruise specific fuel consumption
$\left(\frac{L}{D}\right)$	Cruise lift-to-drag ratio

Table 7: Driver parameters of NASA method [2].

The DOC formulas are derived from ATA method "*Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Planes*" [1]. It was developed in the 40s, but it was continuously reviewed until the 1967. ATA used data from airlines' costs and from manufacturers' experience. Those formulas were developed for subsonic and supersonic (with a cruise Mach number lower than 5) aircraft. NASA extended these equations to high hypersonic aircraft using extrapolation and introducing new factors.

4.2 DOC formulas

The Direct Operating Cost equations are the most important part of the work.

The NASA method splits the total direct operating costs relationship in six elements. Each of them describes a cost item of the direct operating cost of the aircraft. These parts are:

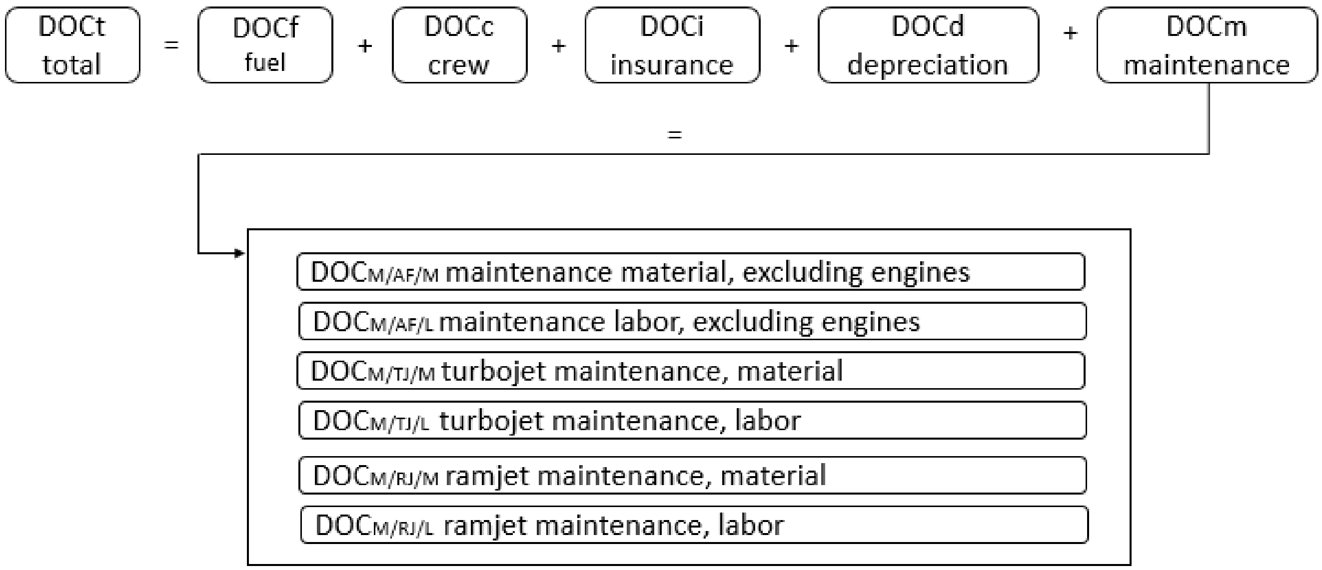


Figure 48: DOC Formula Summary [17].

The generic formulation of the NASA modified ATA CERs is:

$$DOC_i = a_i \frac{W_{AF}}{W_{GTO}} * b_i \left(\frac{W}{T}\right)_{TJ} * c_i \left(\frac{W_{RJ}}{Ac\; C_{TRJ}}\right) * d_i\; sfc * e_i \left(\frac{L}{D}\right)$$

The equations have the form of product of the drivers and some numerical coefficients. These ones change according to the different system of units, because of the conversion factors. In most equations, the drivers are contained in other two terms: the ratio between the fuel mass and the maximum take-off weight $\frac{W_{fT}}{W_{GTO}}$ and the ratio between the payload mass and the maximum take-off weight $\frac{W_{PL}}{W_{GTO}}$. Indeed, it is possible to write that:

$$\frac{W_{fT}}{W_{GTO}} = f\left(sfc, \left(\frac{L}{D}\right)\right)$$

$$\frac{W_{PL}}{W_{GTO}} = f\left(\frac{W_{AF}}{W_{GTO}}, \left(\frac{W}{T}\right)_{TJ,}, \frac{W_{RJ}}{Ac\; C_{TRJ}}\right)$$

The equations are in $cent_{1972}/ton\, mile$. It is possible to use both the International System of unit and the English Systems of units, chancing properly the numerical coefficients.

Direct operating cost of fuel

One of the greatest cost item is the cost of fuel and it is necessary to evaluate it in the best way as possible. The NASA equation for evaluating the direct operating costs of the fuel is:

$$\mathrm{DOC_{Fuel}} = \frac{1460\ \mathrm{C_f}\left(\frac{\mathrm{W_{fT}}}{\mathrm{W_{GTO}}}\right)(1-\mathrm{K_R})}{(\mathrm{LF})\ \left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

Where:

$\mathrm{C_f}$ = cost of fuel per unit weight, [$/kg];

$\mathrm{W_{fT}/W_{GTO}}$ = fuel weight fraction;

$\mathrm{K\_R}$ = reserve fuel fraction (usually defined by legislation); it is a percentage of total fuel weight and it should be less than one;

LF = average load factor;

$\mathrm{W_{PL}/W_{GTO}}$ = Payload weight fraction;

If you prefer to use English units, the 1460 should be replaced by 2000

The load factor is a value between zero and one. It is the average payload carried compared to the total payload mass that could be boarded. The reference [2] suggests that for the hypersonic aircraft, the value for the load factor can be 0.6. Despite the ATA relationship, NASA CER has the term of fuel fraction.

Direct operating cost of crew

The second cost item in the DOCs is the cost of crew. This cost is about the cost of the cockpit crew, without considering the flight attendants. It considers not only the wage of the pilots and co-pilots, but also their benefits and their travel expenses. The equation for the evaluation of the direct operating costs of the crew is:

$$\mathrm{DOC_{Crew}} = \frac{320}{0.725\ (\mathrm{LF})\ \left(\frac{\mathrm{W_{PL}}}{\mathrm{WGTO}}\right)\mathrm{M}\ \left(\frac{\mathrm{V_B}}{\mathrm{V_{CR}}}\right)}$$

Where:

$\mathrm{W_{PL}}$ = payload weight, [kg]

M =cruise Mach number

V_B/V_{CR} = ratio of block velocity to cruise velocity

The 0.725 should be replaced by 0.34, if you prefer to use the English Units

This equation considers the crew salary, fringe benefits, training programs and travel expense of the crew. The numerator is the estimation of the hourly cost of the cockpit per block hour for a hypersonic aircraft. It is by extrapolation of an ATA relationship of the cost of cockpit for subsonic turbojets. This value should be update for evaluating the DOC of crew for different years. In the case of the LAPCAT A2 cost estimation, the value has been replaced by the what it is suggested by reference [5]. It gives a formulation for the evaluation of the hourly cost of the cockpit. The wage of the pilots depends also on the technical features of the aircraft. The hypersonic aircraft can be assimilated to space vehicle. For this reason, the crew salary is higher than the case of subsonic jet.

The Stewardess' cost is not considered because it is classified as indirective operating costs. It is a passenger service costs and it cannot be associated with a specific aircraft. 7

Direct operating cost of insurance

The insurance is necessary, because it is not possible fly without. The insurance indemnifies the airline and the third-parts from damages and injuries. The equation for the evaluation of the direct operating costs of insurance is:

$$\mathrm{DOC_{Insurance}} = \frac{(\mathrm{IR})\left(\frac{C_{HST}}{W_{GTO}}\right)}{0.725\ (\mathrm{LF})\left(\frac{W_{PL}}{W_{GTO}}\right) \mathrm{M} \left(\frac{V_B}{V_{CR}}\right) \mathrm{U}}$$

Where:

IR = annual insurance rate, [%/100]

C_{HST}/W_{GTO} = ratio, cost of airplane (total) to gross take-off weight, [$/kg]

U = aircraft utilization, [bhr/yr]

For the English units, the 0.725 should be replaced by 0.340.

The utilization is the number of block hours flown per year. It can be evaluated knowing the block time and the number of flights per years. In the aeronautic, the block time or block hours are the time from the wheel blocks are removed before the taxi and take-off to those blocks are repositioned again and the engine are shut down. The annual insurance rate it is difficult to estimate, because it depends on the legislation and on the airline policy. In a first approximation, it can be expressed as a percentage of the total vehicle cost. During the life of vehicle, this coefficient decreases quickly. For a hypersonic aircraft, it should be considered a different value from civil airplane, because the presence of high level technologies on board and the reaching of speed that could be a risk both for passenger than for the airplane. The insurance cost of a hypersonic vehicle is higher than the one of a subsonic jet.

Direct operating cost of depreciation

The depreciation is linked to the loss of the aircraft value during its operating life. During the depreciable period the vehicle loses values each year. The depreciable life depends on the policy of the airline and on the technologies on board. At the end of the period, the airplane has not economic value. This happens with all goods and it is associated a cost. The equation for evaluating the direct operating costs of depreciation is:

$$DOC_{Depreciation} = \frac{1.1\left(\frac{C_{HST}}{W_{GTO}}\right) + 0.3\left(\frac{C_{TJ}}{W_{GTO}} + \frac{C_{RJ}}{W_{GTO}}\right)}{0.725\ (\mathrm{LF})\ \left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{M}\ \left(\frac{\mathrm{V_B}}{\mathrm{V_{CR}}}\right)\mathrm{U}\ \mathrm{L_d}}$$

Where:

$\mathrm{C_{TJ}/W_{GTO}}$ = ratio, cost of turbojet engine set per aircraft to gross take-off weight, [$/kg]

$\mathrm{C_{rJ}/W_{GTO}}$ = ratio, cost of ramjet engine set per aircraft to gross take-off weight, [$/kg]

$\mathrm{L_d}$ = depreciation life of aircraft, [yr]

For the English units, the 0.725 should be replaced by 0.34.

The depreciation cost is linked with recovering the initial costs of the airplane over a defined depreciation life. This period for hypersonic aircraft is 10 years. It is shorter than the value of subsonic aircraft (that is about 15/20 years). This is due to the fact that the high-level technologies on board lose their value more rapidly than a traditional aircraft.

Direct operating cost of maintenance

The maintenance is an aspect that is related to the overall vehicle for all its operating life. The direct operating cost of maintenance should be divided in parts to evaluate better the different factors. The DOC of maintenance is split in six different relationships. Four of them are about the direct operating costs of the engines (that are one of the most relevant technologies of hypersonic aircraft) and two of them are about the DOCs of rest of airplane (i.e. airframe and systems). The equations consider the materials needed to the maintenance and the labor of personnel. They are:

$$\mathrm{DOC_{Maintenance}} = \mathrm{DOC_{M/AF/L}} + \mathrm{DOC_{M/AF/M}} + \mathrm{DOC_{M/TJ/L}} + \mathrm{DOC_{M/TJ/M}} + \mathrm{DOC_{M/RJ/L}} + \mathrm{DOC_{M/RJ/M}}$$

Where:

$M/AF/L$ = airframe and subsystems maintenance labor, excluding engine

$M/AF/M$ = airframe and subsystems maintenance material, excluding engines

$M/TJ/L$ = turbojet maintenance labor

$M/AF/M$ = turbojet maintenance material

$M/RJ/L$ = ramjet maintenance labor

$M/AF/M$ = ramjet maintenance material

The first term of $DOC_{\mathrm{Maintenance}}$ is the direct operating costs of airframe and subsystems maintenance labor:

$$\mathrm{DOC_{M/AF/L}} = \frac{(3.22 + 1.93\ \mathrm{t_f})\left[0.05\ \left(\frac{\mathrm{W_{AF}}}{\mathrm{W_{GTO}}} + \frac{\mathrm{W_{AV}}}{\mathrm{W_{GTO}}}\right) + \mathrm{coef}\right]\mathrm{M}^{\frac{1}{2}}\,(\mathrm{r_L})}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

Where:

t_F = time of flight, hours

W_{AF}/W_{GTO} = aircraft weight fraction (excludes engines and avionics)

W_{AV}/W_{GTO} = avionics weight fraction

r_L = average maintenance labor rate for all personnel, $

$coef$ = it is a coefficient that depends on the weight of the aircraft

$$coef = \left(\frac{6}{W_{GTO}} - \frac{630}{\left(\frac{W_{AF}+W_{AV}}{10^3}+120\right)W_{GTO}}\right) * 10^3$$

For the English units, 2 and 1.2 should be used instead 3.22 and 1.93

The second term of DOC of maintenance is the cost of the airframe and subsystems maintenance material:

$$\mathrm{DOC_{M/AF/M}} = \frac{(4.52\ \mathrm{t_f} + 9.04)\left(\frac{\mathrm{C_{HST}}}{\mathrm{W_{GTO}}} - \frac{\mathrm{C_{TJ}}}{\mathrm{WGTO}} - \frac{\mathrm{C_{RJ}}}{\mathrm{W_{GTO}}}\right)}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T} * 10^3}$$

The terms present in this equation are the same of the previous one.

For the English units, 6.2 and 12.4 replace 4.52 and 9.04.

The third component of the DOC of maintenance is the cost of turbojet maintenance labor is:

$$\mathrm{DOC_{M/TJ/L}} = \frac{\left(\frac{\mathrm{T}}{\mathrm{W}}\right)_{\mathrm{GTO}}\ (1 + 0.3\ \mathrm{t_F})\left(\frac{8.60}{\mathrm{T_{TJ}} * 10^3} + 0.087\right)\mathrm{r_L}\ \mathrm{K_{LTJ}}}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

Where:

$\left(\frac{T}{W}\right)_{GTO}$ = thrust to weight ratio at take-off

$\mathrm{T_{TJ}}$ = thrust of turbojet engines per engine (sea static level), N

$\mathrm{K_{LTJ}}$ = ratio, maintenance labor for HST turbojet engines to subsonic engines.

For the English system of units, 1.2 and 0.054 replace 8.6 and 0.087.

The term of the direct operating cost of turbojet material is:

$$\mathrm{DOC_{M/TJ/M}} = \frac{\left(\frac{\mathrm{C_{TG}}}{\mathrm{W_{GTO}}}\right)(0.11\ \mathrm{t_F} + 0.029)\ \mathrm{K_{MTJ}}}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

Where:

$\mathrm{K_{MTJ}}$ = ratio, maintenance material for HST turbojet engines to subsonic engines.

In this case for the English units, you should use 0.015 and 0.04 instead of 0.11 and 0.029.

For fling at hypersonic speed, it is not possible to use turbojets. They can reach about Mach 3. It is necessary to use ramjet engines. For this reason, the equation for the DOC of maintenance should considers also the aspects of the maintenance of the ramjet/scramjet. The part linked to direct operating cost of the ramjet maintenance labor is:

$$\mathrm{DOC_{M/RJ/L}} = \frac{(1+\mathrm{t_F})\left(\dfrac{0.876\ \mathrm{N_{RJ}}\left(\frac{\mathrm{L}}{\mathrm{D}}\right)}{\mathrm{W_{GTO}}/\ 10^3} + 0.087\right)\mathrm{r_L}\ \mathrm{K_{LRJ}}}{\left(\frac{\mathrm{L}}{\mathrm{D}}\right)(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

Where:

L/D = cruise lift to drag ratio

$\mathrm{N_{RJ}}$ = number of ramjet modules per aircraft

$\mathrm{K_{LRJ}}$ = ratio, maintenance labor for ramjet engines to present subsonic turbojets engines.

The document is not clear about the numerical coefficients for the English units of measurement. In this case is better to use the International System of units.

The last cost item of the DOC of maintenance is the direct operating cost of ramjet material; it is:

$$\mathrm{DOC_{M/RJ/M}} = \frac{\left(\frac{\mathrm{C_{RG}}}{\mathrm{W_{GTO}}}\right)(0.036\ \mathrm{t_F} + 0.029)\ \mathrm{K_{MRJ}}}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

Where:

$\mathrm{K_{MRJ}}$ = ratio, maintenance material for ramjet engines to present subsonic engines.

For the English units, 0.05 and 0.04 replace 0.036 and0.029.

In the reference [1], there are not the equation for the evaluation of the direct operating costs of the ramjets, because it gives a mathematical model for subsonic and sonic jet. The NASA has gathered the equations for the DOCs of the ramjet from the ones of turbojet, substituting the parameter about the last type of engine. indeed, according to the reference [2], it is possible to replace the thrust-to weight ratio at the take-off $\left(\frac{\mathrm{T}}{\mathrm{W}}\right)_{\mathrm{GTO}}$ whit the reciprocal of lift-to-drag ratio $\left(\frac{\mathrm{L}}{\mathrm{D}}\right)^{-1}$. The turbojet thrust $\mathrm{T_{TJ}}$ is substituted by the term $\frac{\mathrm{W_{GTO}}}{\frac{\mathrm{L}}{\mathrm{D}}}$. The last term is divided by the number pf ramjets $\mathrm{N_{RJ}}$ to make the equivalent of the thrust of turbot that is applied to each engine.

The equation of maintenance is the most complex, because it is split in parts for considering each relevant aspects of maintenance. It emphasizes that the propulsion is one the most critical, but fundamental, features of the hypersonic vehicle. Those maintenance equations come from industry's data of airline maintenance costs. For the engines relationships, there are coefficients that compered the maintenance of hypersonic engines with subsonic turbojets of comparable size and thrust. This is due to the fact of there are not data about the maintenance of hypersonic aircraft, and the engine are tested alone and not integrated in the aircraft. These terms are not representative of higher purchase spares' cost for hypersonic engines, but they compare the cost of high level engine with subsonic ones.

4.3 Analysis of some relevant coefficients of the cost estimating relationships

In the CERs are present some relevant coefficients that should analyze deeper, because they are not so common or easy to obtain.

The load factor LF is a ratio between the average payload carried in each flight and the total payload that can be on board. Indeed, not all the flights have the maximum payload that can be carried for each flight. For the economic evaluation, it is important to define an average value of the payload. It can be gathered from the market analysis and statistics. The NASA report suggested to use a value of 60% for a hypersonic aircraft.

The utilization U is the average block hours per year. It can be evaluated considering the number of flight of each year and the block time. In the case of the baseline, it is considered 3000 hours of utilization per year.

Another important factor is the fuel costs C_f. It can change the direct operating cost in a meaningful way, because DOC of fuel is the main cost item. The fuel used by the baseline is liquid hydrogen. It is difficult to estimate its price per unit of weight, because now it is not produced in large amounts. The advantage of the equation of DOC of fuel is not to depend on the fuel type. Indeed, the only term linked to the type of fuel is the cost per kilogram. If the fuel changes, it is necessary to modify only this term.

The insurance cost is estimated as a percentage of the initial acquisition cost of the aircraft. The value is defined by the insurance rate IR . At the beginning of the life of the aircraft, the insurance rate is about the 5% and it decreases at 2 % in few years. For the baseline it is used the last value.

Another term necessary for the estimation is the depreciable life L_d.A typical value for the depreciation period of subsonic jet is about fifteen years. For the hypersonic baseline, it is chosen ten years for the high level of the technologies on board that could lose their value more quickly.

In the equations of the maintenance labor, it is present the labor rate r_L. It is the hourly wage of the maintenance personnel. Considering value indicated in the ATA equations of t1967 and a growth due to different year for the estimation (1972), the value used for the estimation is 5.30 $/hr. this vale cannot be correct for the direct operating cost estimation of the LAPCAT A2. Thanks to reference [39], it is possible to obtain the hourly salary of the maintenance workers at the 2016.

The acquisition cost of the aircraft can be evaluated considering the cost of the all components of the vehicle and it can be estimated in various way. The NASA method considered the cost of the airframe, the cost of avionic and the cost of engine, splitting the turbojet from the ramjet.

$$\frac{C_{HST}}{W_{GTO}} = \frac{C_{AF}}{W_{GTO}} + \frac{C_{TJ}}{W_{GTO}} + \frac{C_{RJ}}{W_{GTO}} + \frac{C_{AV}}{W_{GTO}}$$

Other important coefficients are the ones of the maintenance of the engines. In the equations of the maintenance, the coefficients K_{LTJ}, K_{MTJ}, K_{LRJ} and K_{MRJ} are introduced. All these parameters are ratios to link the maintenance requirements of hypersonic engines with the maintenance of large subsonic turbojets. The subscript L is about the labor required for maintenance and the subscript M is about the material needed for the maintenance. The coefficients of material do not aim to consider the increase of material cost and of parts but the fact that the frequency of replacement increases. K_{LTJ}, K_{MTJ} have a value of 2, due to the higher operating temperature than a subsonic turbojet. For the ramjet coefficient of material, it is chosen the value of 3 and, for the one of the labor, the value is 2. The last type of engine has not rotative parts and the maintenance can be easier. On the other hand, it is exposed to the higher thermal load.

4.4 Direct Operating Costs' estimation for the NASA baseline

In the *Table 8*, there is the DOC evaluation for the baseline using the NASA method. It is interesting the comparison with a large subsonic jet as a Boing 747. For this aircraft estimation of DOC, the ATA method [1] is used. It is assumed an average load factor of 60%.

		Cost Per Ton-Mile (cent 1972/ton-mile)	
	DOC Element	Baseline HST	Large Subsonic Jet (B747 Class)
Fuel	DOCf	25.7	5.0
Crew	DOCc	1.0	1.5
Insurance	DOCi	2.1	0.7
Depreciation	DOCd	12.0	2.9
Maintenance	DOCm/af/l	0.6	0.6
	DOCm/af/m	1.5	0.5
	DOCm/tj/l	0.2	0.3
	DOCm/tj/m	0.9	1.1
	DOCm/rj/l	0.4	
	DOCm/rj/m	2.4	
	DOCm total	6.0	2.5
TOTAL		46.8	12.6

Table 8: DOC for HST baseline and large subsonic jet, comparison [7].

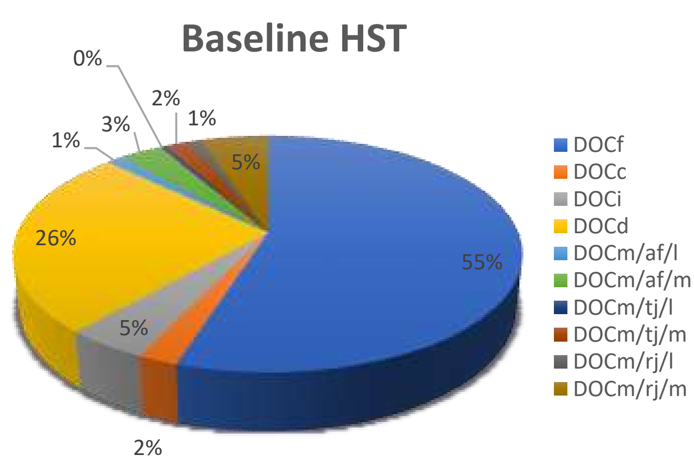


Figure 49: Baseline HST Direct Operating Costs

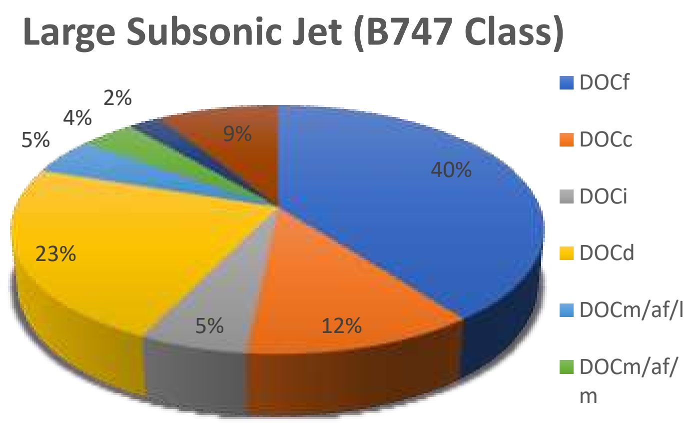


Figure 50: Large subsonic jet Direct Operating Cost

The direct operating costs for the baseline are higher than a subsonic large jet. In both cases, the major cost item is the cost of the fuel. The depreciation is also very relevant in both of cases. It is about the 20%. The direct operating cost of the insurance has the same percentage for both aircrafts. It is the 5% of the total direct operating cost. What is very different between the two aircrafts is the cost of the crew. In the case of the subsonic jet, it is about the 12 %. For the hypersonic aircraft is only the five percent. For the baseline HST the maintenance is about the 7%. The cost linked to the material is greater than the ones of maintenance. In the case of the subsonic jet the maintenance is around the 20%. The most important part is the cost of maintenance of turbojet material. For the subsonic jet, there are not ramjet engine. For this reason, the cost of ramjet maintenance is not present for the subsonic jet.

4.5 Considerations about Direct Operating Costs

In this last part, there are some consideration about the direct operating cost relationships. For each equation, it is evaluated which drivers can influence most the direct DOCs. Before analyzing each CER, there are some notes about Major technological improvements and changes, that should be considered for a hypersonic vehicle.

Major technological improvements and changes

First of all, the propulsion system is what characterizes a hypersonic vehicle. As in the case of the LAPCAT project, it is what drives the work. Behind the idea to develop hypersonic airplane, there is the proposal to design an aircraft completely reusable and that is able to have the same mission of a traditional aircraft, fling more than one times per day. The choice of using airbreathing engines aims to do this. As said before, it is not possible to use hydrocarbon fuels, because they do not permit to reach the high speed. It should be used liquid hydrogen, that is the best choice for its chemical properties. In the figure below, it is possible to see the different specific impulse of various types of engines considering the hydrocarbon fuels or the liquid hydrogen fuels.

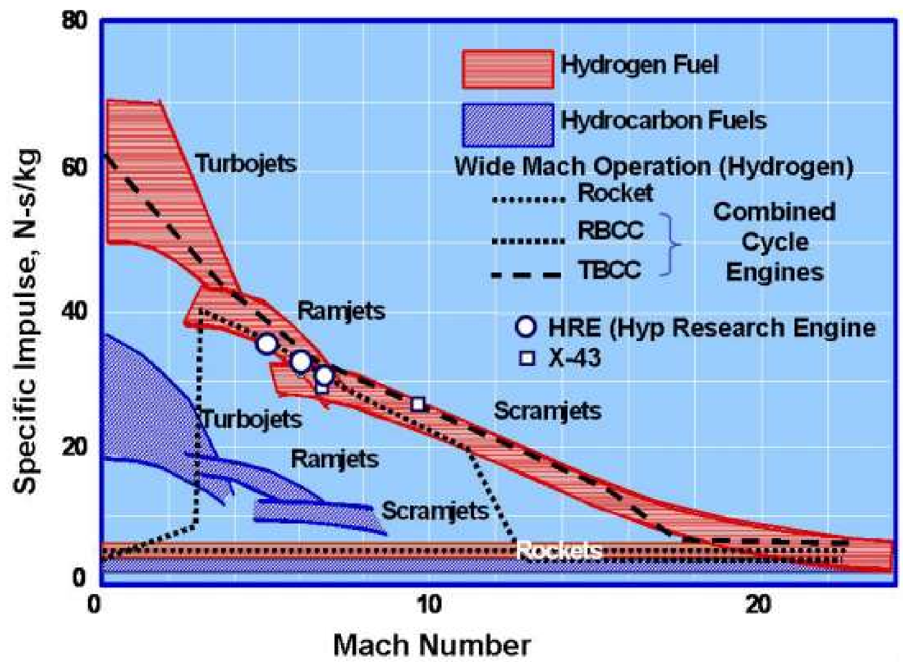


Figure 51: Hypersonic engine efficiency [40].

The LH2 is cryogenic. It could cause some problems during the refueling phase at the airport and it forces to review some legislation rules.

Also, the procedures and the infrastructures of the airport should be modified, considering both the fact of the use LH2 and the operating features of the aircraft. In fact, during the flight the airplane is undergone at high thermal load. After the landing, it could have very hot structures. All the operations, as the disembarking of passengers, maintenance or refueling can not be done in the same way of a traditional aircraft. As the LAPCAT vehicles shows, usually these aircrafts do not have the same configuration or dimension of a traditional jet. So, different infrastructures and runway are required.

Another important aspect that should be considered is the mission profile. For hypersonic aircrafts there will be limitations to fly over populated countries, for the noise's problem and the sonic boom. Traditional routes cannot be used and new courses should be considered. The mission profile also changes because of the rules, the limitations and the engines features. For instance,the LAPCAT MR2 has two types of engine: the ATR for the low speed flight and the DMR for the hypersonic speed flight. During the mission, it is necessary to fly to a constant altitude to start the engines. The last phase of the flight is done with a minimum level of thrust, almost gliding. The cruise altitude is higher than the one of a traditional jet.

Another important aspect is the hypersonic aerodynamic. Few data are now available and some experimental texts are necessary to create a database. It can give the possibility to develop a simulation tool. The overall performances of a hypersonic aircraft depend a lot from the aerodynamic efficiency, i.e. the lift-to-drag ratio, that impacts also on the propulsive performances. The development of lifting body configuration or of waverider configuration aims to increase the aerodynamic efficiency during the high-speed flight.

During a hypersonic flight, the thermal load could cause some problem. The reference [37] analyzes the temperatures of the inner and outer wall of tank along the interfaces with the cabin, the aeroshell and the propulsion plant for the LAPCAT A2 and LAPCAT MR2 mission.

It underlines the necessity of the introduction of new materials with high-performances. Indeed, it shows that the external wall's temperature has the same growth of the flight speed for the highly non-linear heat radiation. The convective heat transfer reaches a level after that it does not increase with the third power of the speed, but it has a stable value. In particular this happens for aeroshell with a high emissivity. With the growth of the flight speed, the value of integrated heat load is lower, because it is lower the time for the thermal load to penetrate the structure. A metallic skin has some problems as the fact that it is too heavy and it needs active cooling system (that is heavy too). It can be used only below Mach 4. The introduction of carbon matrix composites can be a better, considering the fact of they can be used also for hypersonic speed.

Another aspect that should be considered is the operating costs. The directive operating cost could change a lot. The maintenance cost can increase than a subsonic jet considering the high technological level of the aircraft and its peculiar configuration. The most relevant aspect is the fuel costs. As shown in the reference [19], the cost of fuel is influenced by the production method of LH2. It can be reduced to a third if the hydrogen is produced by steam reforming of hydrocarbon rather than electrolysis. Reducing a cost can be very attractive for the customers and the number of investments on the project can increase a lot.

Technological aspect that should be considered in the CERs

It is important to consider that the equations of the NASA method are for a point-to-point vehicle that flies in atmosphere. If the DOC evaluation is for a parabolic vehicle or a suborbital spaceplane, the equations does not give a correct estimation. For these different mission profile, it is necessary to determine the validity of the CERs of the reference [2]. If they are not adequate, it is possible to introduce corrective factors or using an alternative method for the evaluation of the direct operating costs of the vehicle.

The first cost item is the DOC fuel. As shown in *Figure 49*, it is the most relevant part of the direct operating costs of a hypersonic vehicle. The drivers that should be taken into account are:

- The cost of fuel
  According to the type of fuel, its cost per kilo can vary widely. In the case of LH2, the method of production (electrolysis of water or utilization of other sources as hydrocarbons) and the productive scenario (that means the production rate and the technological level of the productive plant) have a great impact on the cost, as underlined by reference [19]. The productive scenario is directly linked with the technological progress. Indeed, it shows how many fuel can be produced by the production plant. If the quantity of fuel produced is greater, price would be lower. Another

important aspect is the production country. The cost of energy in the United States is the half of the cost of Europe. This bring a reduction of the fuel production cost and of its price on market.

- The propulsive system
  Many different combinations of propulsive systems can be tested for reaching hypersonic speed. All of them have different performances, as the specific impulse or the specific fuel consumption. These features and the operating modes of the engines can modify the quantity of fuel necessary for the mission and subsequently the direct operating cost of fuel.
- The use of innovative materials
  The introduction of innovative material can change the weight of the vehicle components. In the equation for the evaluation of the direct operating cost of the fuel, there is a link with the weight of fuel, the weight of the payload and the ground take-off weight. To reduce the weight of the structure can increase the quantity of payload on board and the profits for the airline company.
- The structure configuration
  The hypersonic aircrafts have peculiar structure configuration. The optimization of the fuselage shape can bring great advantages in the reduction of the drag and of the fuel consumption. The waverider configuration is used to increase as much as possible the aerodynamic efficiency. The increasing of the lift can be a great advantage for the overall performances. The consumption of the fuel can be reduced.
- The legislation
  The quantity of fuel that should be embarked depends on legislation requirements. Its value is linked to the dimension of the tanks and the time to reach an alternative airport, if the designed one is not available. The extra quantity of fuel depends also on the fuel policy of the airline company.
- Mission profile
  The traditional routes are not available for hypersonic plane. So, different mission paths required different amount of fuel. The fact of the mission profile of hypersonic aircraft is different from the one of subsonic jet can bring changes in the quantity of fuel on board. The high-speed aircrafts need a first phase of flight at subsonic speed for moving away from populated areas, avoiding the sonic boom. The climb to the cruise altitude is divide in step to give the possibility to the engines of reaching the right operating mode and the hypersonic speed.

The direct operating cost of the crew includes salaries, fringes, benefits, training program and travel expenses of the members of the crew. The cost of flight attendants is considered a service to passengers and it is an indirect operating cost. The wage of the crew depends on the type of vehicle and its performances. If the speed or the maximum take-off weight increase, the salary of the crew also increases. In the case of hypersonic airplane, it should be considered that the technologies on board (including the propulsion system) are closer to a space vehicle than a civil aircraft. This increases considerably the wages of the pilots. The crew members should be well trained to fly with a not conventional aircraft. This increases the cost of training that is a cost item of the direct operating cost of crew.

In the NASA DOC equations, the insurance cost is evaluated as a percentage of the initial acquisition cost of the vehicle. The insurance protects the company from the risks of aviation. In case of accident, the insurance gives the possibility to refund people and company for damage to the structure and to passengers. Increasing the number of passengers on board, the insurance cost increases too. Another important aspect that should be considered is the use of new technologies closer to the space field. They grow the insurance rate. In the NASA equation there is dependence from use of aircraft. The hypersonic vehicles bear high thermal load. After the landing, the structures could be at high temperatures. It is not possible to do the same operations of a traditional aircraft. The time of stop of vehicle could be more. The introduction of innovative materials able to disperses the heat more quickly will increase the utilization of the aircraft and amortize better the insurance costs.

The depreciation life of an aircraft is difficult to estimate. According to the reference [11], it depends on many factors as:

- Intended life of the fleet type being operated by the airline
- Economic estimation made by the manufacturers
- Changes and evolution in technology
- Company policies about repairs and maintenance
- Aircraft operating life
- Markets trends

A hypersonic aircraft has high-level technologies and it is possible that its depreciation life is shorter than a traditional subsonic jet.

The last equation is about the maintenance costs. In the NASA method, there is the division between engines and airframe for evaluating the cost of maintenance. For each of these two categories, it is considered the contribution linked to the labor of workers and to the materials. In the case of labor, the wage of the laborer increases, considering the high-level specialization required for both the structure and each system on board. The cost of material increased considering the introduction of innovative materials for all parts of the structures. The hypersonic speed and high thermal load oblige to do more replacement and maintenance activities to all the structures and to each component. In the NASA equation, the cost of maintenance material is directly linked to the acquisition price of vehicle. The preliminary economic studies on hypersonic aircrafts show that acquisition cost of this vehicle is higher than the one of traditional jet. It is strongly dependent on the cost of technologies on board. In the case hypersonic vehicle, they are very expensive, because are new and, sometime, comes from the space field

5. Technological impact on DOC

In this chapter, there is a deeper analysis of the NASA mathematical relationships of the reference [41], to write a new set of equations allowing the evaluation of the impact of technologies on direct operating costs. In these new relationships, the link between new technologies and the DOCs for a hypersonic aircraft should clearly appear. An important part is the analysis of each cost driver of the NASA equation, for understanding whether and how it can change the direct operating costs. According to the reference [41], the driver is a technological parameter of the DOC equation that is directly connected to hypersonic technology and that has a significant effect on the direct operating costs.

The first section of this chapter introduces the importance to have a cost estimation from the beginning phases of project. At this stage of the project, few data are available, but with the appropriate mathematical relationships it is possible to do a preliminary analysis of the costs.

After that, there is an analysis of the NASA equations' drivers to understand better their impact on the direct operating costs.

From a first assessment, the most interesting equations from a technological point of view seems to be those of fuel and of maintenance. For this reason, in the third part of the chapter, they are in-depth analyzed. For the equation of fuel, the aspect of the fuel price is examined. In the case of the equation of maintenance, many drivers should be investigated and I is for this reason that we suggested the use of QFD method.

In the last two sections of the chapter, all NASA equations, excluding the crew one, are rewritten to make visible the drivers and their effect on the DOCs. For the equation of the fuel and maintenance, Breguet equation is exploited to formalize the relationship between important technological parameters. It is very interesting because two involved parameters are the aerodynamic efficiency and the specific fuel consumption which are directly linked with new technological aspect of hypersonic vehicle.

5.1 Importance of evaluation of Direct Operating Costs

The development of a new set of equations for the direct operating costs estimation is very interesting from different points of view. One of them is the opportunity to link directly the new hypersonic technologies with the operating costs. This will give the possibility to understand how the DOCs are influenced by the changes on the vehicle's structure and equipment. This will be useful for the designers to create a cost-effective product. At the initial phases of project, the engineers can evaluate the direct operating costs that a company should sustain to make the airplane operating and which changes may reduce the impact of this item of the life cycle costs. For the airline companies, it is important that the operating costs are as lower as possible to increase their profits.

The evaluation of the costs of an airplane is difficult because the aircraft will be placed in service many years after the design phase. The economic conditions will be different than the ones considered during the design phase. Some changes will be made in the production of the parts, changing the preliminary cost estimations. In case of hypersonic aircraft, there are not any airplanes on service, that can be used as references for the costs estimation. Thus, costs are evaluated using mathematical models, but It is not possible to compare the results obtained from a mathematical model with the ones come from market data. The only possible solution is to compare the results coming from the exploitation of different estimation models and try to understand similarities and limits of application.

The first costs analysis is made at the beginning of the project and only few data are known and available. The relationships used for the first costs estimations shall only use the parameters that can be obtainable at the preliminary design, as weights or thrust of engines. They should be as precise as possible, because in the preliminary phases of the design there is the allocation of the greater part of costs. In this phase, the designers are free to make changes without threatening the production phase. A good cost estimation method can help the engineers taking the right decisions for the production of a cost-effective product.

The starting point is a deeper analysis of the NASA equations of the reference [41] and in particular of the effect of the cost drivers of those formulas on the DOCs. The first step is to evaluate which equations can be most influenced by the new technologies. After that, it is analyzed which factors can impact deeper on the equations considered. Different tools are used for the analysis. One of them is the QFD analysis.

The NASA equations are rewritten exploiting the Breguet equation for the range. This relationship makes possible to evaluate the influence of engines performances on the direct operating costs. The engine is probably the most relevant feature for a hypersonic aircraft. One example is the LAPCAT project, where the engine configuration drives the development of the all vehicle. In the NASA report [41], there are some relationships for evaluating the acquisition cost of the vehicle, which is given by the sum of the acquisition costs of each part. The acquisition price is directly linked to the technological features of the aircraft. The formulas of reference [41] permits to evaluate the acquisition costs, even if few data are available, because the weights of the aircraft, the number of engine and the cruise Mach are involved. These data are usually available from the beginning phases of the project. It is possible to evaluate the variation of the acquisition price with the changes of this design parameters.

5.2 Analysis of the Direct Operating Costs.

The operating costs are the costs that occur when the aircraft is on service. They can be divided in indirect operating costs and in direct operating costs. The latter can be directly linked with the aircraft operations, and the first ones depends on the policy of the airline company. In the NASA report [41], there are the relationships for the estimation of the direct operating costs. The cost items are:

- Direct operating cost of the fuel
- Direct operating cost of the crew (flight attendants are not considered)
- Direct operating cost of insurance
- Direct operating cost of depreciation

- Direct operating cost of maintenance

In the case of the direct operating cost of fuel, the most important factor is the cost per unit of weight of the fuel. The hypersonic aircraft can use liquid hydrogen to reach their performances, because that fuel has high specific energy content. Now, liquid hydrogen as a fuel is not available in a great quantity and the production plants should increase their production capacities. Its price depends on different factors, such as the different production rate and the techniques of production.

The cost of maintenance considers both the contribution of the engines and of all the other components of the aircraft (i.e. the airframe). For each of them is evaluated the costs of maintenance labor and of the maintenance material. The labor item includes the works of the employees and it is dependent on the hourly salary of maintenance workers. The material cost is linked to the acquisition cost of the vehicle or of the engine and it considers the costs of the spare parts. It does not show the increasing price of the spearing parts but the fact that the components should be changed more frequently in a hypersonic aircraft than in a subsonic jet. The greater complexity of the maintenance of hypersonic aircraft is taken into account thanks to appropriate coefficients that consider the additional time required for maintenance and the frequency of replacement of the parts of a hypersonic aircraft. For the engines, it is considered the presence of turbojets for fling at lower speed and the ramjets to fly at high Mach number. So, different coefficients are introduced in the equations. The maintenance equations depend on many cost drivers, because the maintenance is an aspect that concerns all the parts of the vehicle. It is difficult to identify which parameter can have a great impact on the cost of maintenance in a preliminary phase of the work.

The relationships of the crew, insurance and depreciations are closely associated with the economic choices of each company.

For instance, the cost of the crew depends not only on the wage of crew but also on the benefits for the pilots. It is not possible to define a unique value for the hourly crew salary. It depends on some aircraft features, as cruise speed or maximum take-off weight, but each airline can define its own rules or the salary. Table *9* shows the annual crew wages and salary for the major American airlines. It is possible to see the difference between the companies.

American	$ 214549
Delta	$ 228112
United	$ 214090
Southwest	$ 244437
jetBlue	$ 154502
Frontier	$ 151025
Virgin America	$ 149717
Alaska	$ 131660
Hawaiian	$ 141059
Spirit	$ 120251
Allegiant	$ 116721

Table 9: Average Annual Wages and Salaries - PILOT AND CO-PILOT PERSONNEL ($2016) – data from [39]

In the case of the DOC of fuel, it is more appropriate spiking about cockpit cost per block hour than crew hourly wage. In fact, they include the fringe benefits, the training programs and the travel expense of pilot., The cost per block hour of the cockpit is directly linked with the policy of the airline company too, as it is possible to see in Table *10*.

American	$ 1115
Delta	$ 1261
United	$ 1249
Southwest	$ 963
jetBlue	$ 796
Frontier	$ 705
Virgin America	$ 588
Alaska	$ 782
Hawaiian	$ 945
Spirit	$ 581
Allegiant	$ 669

Table 10: Total Cockpit Cost per Block Hour - ALL AIRCRAFT ($2016) – data from [39]

In the case of depreciation cost, it is relevant the depreciable life, i.e. the years that an airline company decides to use the aircraft before its disposal. Every year, each part of the airplane loses partially its original value. The company can choose to retire the aircraft with a residual value, for reselling it, or not. In the last case, the aircraft is retired and disposed. Usually the depreciation life of an aircraft is between fifteen and twenty years and the residual value is zero [11]. For the hypersonic aircraft, the useful life would be about ten years [41], because the high level of the new technology tends to lose their value more rapidly.

The direct operating cost of the insurance protects the aircraft from the possible risks of damage and accident to itself or to other parts It also gives the possibility to the airline company to refund third parts and passengers in case of accident. The aviation insurance is difficult to estimate, depending on the type of aircraft and the choices of the airline. In fact, each country has its own policy to manage the insurance, even if the safety is guaranteed by the competent authorities [9]. In a first approximation, the insurance cost can be evaluated as a percentage of the acquisition cost of the aircraft. In the NASA method [41], it is suggested a value of 2% of the initial purchase price.

In the next section, it is present an analysis about the effect of the driver on the direct operating cost of fuel and of maintenance. In the first case, it is analyzed the effect of the fuel price. In the latter, it is examined the relationship between the drivers.

5.3 Technological impact on the Direct Operating Cost of Fuel and Maintenance

An analysis of the NASA equation of the cost of fuel and maintenance is performed to understand which technological elements can influence them. For this analysis, Table *11* and Table 15 in which there is an explanation about which aspect of the new technologies can influence the terms of the NASA equations are used.

In the case of the fuel CER, a brief analysis on the evaluation of the price of liquid hydrogen has been performed and it is here reported, because the fuel productive scenario can have a relevant impact the operating costs, as suggested in the reference [19]. The LH2 production does not depend on technologies on board the aircraft, but on the productive plants which are at the ground. The use and the production of Liquid Hydrogen are technological factors related to the Hypersonic vehicle.

The equation of the direct operating costs of maintenance is the most complex, because it consists of the sum of six items. For that reason, it has been necessary to evaluate the possible relationships between the drivers and to define which of them can be considered independent from the others. The QFD tool helps to evaluate which elements are linked together and which type of relationship is present.

After the analysis of the impact of new technologies on the drivers, an alternative formulation of the NASA modified ATA CERs [41] is suggested exploiting the equation of Breguet, because two of its terms are linked to the propulsive strategy and the aerodynamic configuration.

Figure 52 shows the workflow to develop a new formulation for the NASA modified ATA CERs [41].

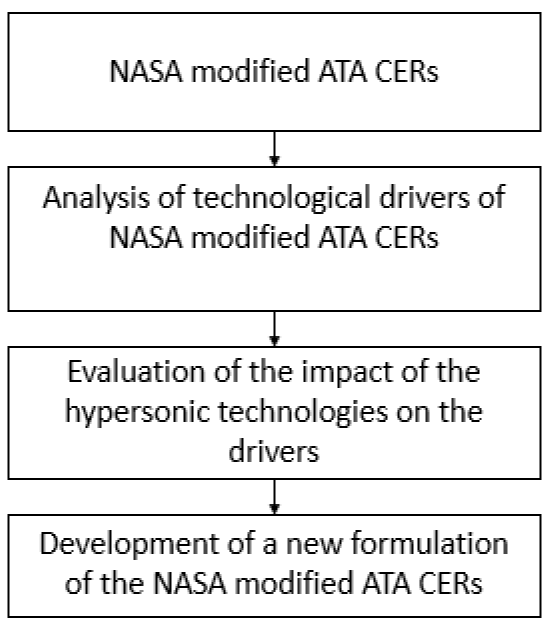


Figure 52: Workflow to develop a new formulation for the NASA modified ATA CERs

Cost Evaluation Relationship of Direct Operating Cost of Fuel

In the NASA report [41], the direct operating cost of the fuel is evaluated as:

$$\mathrm{DOC_{Fuel}} = \frac{1460\ \mathrm{C_f}\left(\frac{\mathrm{W_{fT}}}{\mathrm{W_{GTO}}}\right)(1-\mathrm{K_R})}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

Where:

$\mathrm{W_{fT}}$ is weight of fuel

$\mathrm{W_{PL}}$is the weight of the payload

$\mathrm{W_{GTO}}$ is the maximum take-off weight

$\mathrm{C_f}$ is the unitary cost of fuel.

$\mathrm{R_T}$ is the range of the vehicle

$\mathrm{K_R}$ is the reserve of fuel

All the elements are expressed using units from the International System. This equation is derived from the standard method of estimating DOCs of subsonic jet published by ATA in 1967 [1]. That equation is applicable using all type of fuel, both hydrocarbon than liquid hydrogen, because the fuel features are expressed only by the cost of fuel for unit of weight $\mathrm{C_f}$.

The first step for understanding the effect of the drivers is the analysis of each term of the previous equation.

The most relevant term is the cost of fuel C_f. It is linked with the type of fuel and with the production rate, because different fuels have different price and, in a first analysis, increasing the cost quantity produced, the cost decrease.

In the case of hypersonic aircraft, the fuel can be liquid hydrogen, because with its chemical properties, it gives the possibility to reach the performances required. Reference [42] reports the effect of the production rate on the cost of LH2.

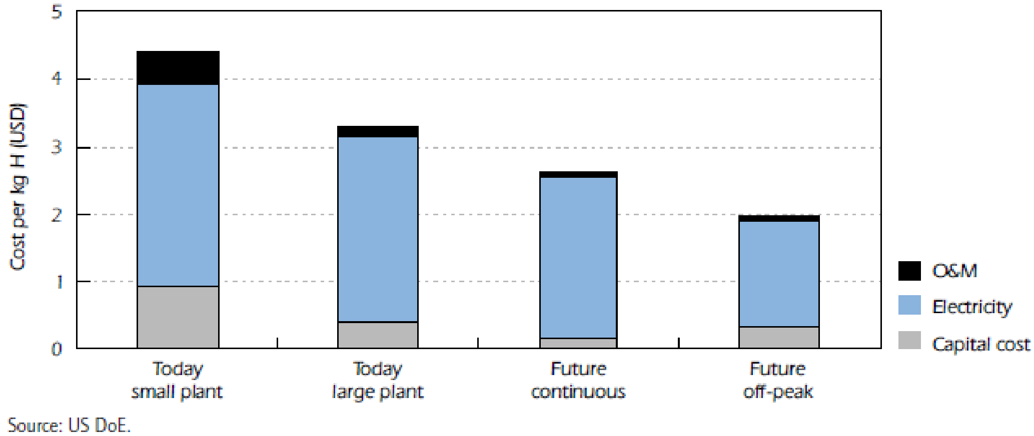


Figure 53: Future potential cost of electrolytic hydrogen [42].

In Figure 53, it is possible to see the trend of the electrolytic hydrogen price for the future. There are four productive scenarios. For each of them, it is associated a specific production rate. The first scenario is the "today small plant" that is linked with production rate of 2.29 tons per day, "Today large plant" is about 10 tons per day. "Future continuous" is about 50 tons per day and 200 tons per day is the case of "Future off-peak". The last scenario shows the maximum production rate associated with the higher technological possibility. The quantity of fuel produced has a very important role on the final cost per kilogram. In the future scenarios, the cost of LH2 is a half of the current price. The final cost of the fuel depends on some factor:

- The capital cost, that is the initial investment on the plant;
- The cost of electricity, necessary to produce LH2
- The cost of operation and maintenance

From Figure 53, it is possible to see that the cost of the electricity is the major component of LH2 cost. The initial investment is higher in the case of high-level technological plant, but it permits to save money both from energy cost and for the operational and maintenance cost.

This is a very simplified analysis, because it is not considered the changes of the economic market. The distribution and the number of the plants are also factors that should be taken into account for evaluating the final price of the fuel [43].

The cost of the fuel can be considered an independent parameter in the equations because it is not linked with the other elements of the equations.

The second term considered is the fuel weight W_{fT}. It is a percentage of the total take-off weight and it is an input set by the user. It should be considered a reserve of fuel K_R as it is required by the legislation, one example is given by reference [44]. The reserve of fuel depends on the flight requirements for reaching an alternative airport in the case of the designed one is not available [45]. Reserve fuel is usually required for:

- A divergent flight over a specific distance

- A holding flight of precise duration at a determined altitude
- Contingency fuel
- An extend duration of the flight

At the preliminary design phases, the only way to estimate the reserve of fuel is considering as a percentage of the total fuel on board, because the details about the mission and the structure of the aircraft are unknown.

Another important aspect characterizing the specific case study is the boil-off of the liquid hydrogen K_{boff}. The LH2 is a cryogenic fuel and the vapor present in the tanks can be useful for having the right temperature in specific zones of the aircraft. It was not considered by the NASA study [41]. Some projects for the development of the future hypersonic aircraft, as the LAPCAT [34], are considering the possibility to use the vapor of the fuel for cooling some parts of the vehicle. This happens for the LAPCAT MR2, that has a specific system, named TEMS, thermal energy management system, for controlling the temperature of the passengers and crew compartment. The passenger compartment is surrounded by small tubes where the vapor of hydrogen can flow. It refrigerates this section of the fuselage. After that, it goes again into the tanks. In the same way of the reserve of fuel, it is estimated as a percentage of the total weight of the fuel. In the case of hydrocarbon fuel this factor is not present.

It is possible to write:

$$0 < K_R < 1$$

$$0 < K_{boff} < 1$$

$$W_{fT}^* = \left(1 + K_R + K_{boff}\right) W_{fT}$$

$$W_{f_t^*} > W_{fT}$$

$W_{f_t^*}$ is the total fuel on board and it considered the contribution of the additional reserve fuel and the quantity of LH2 necessary for the boil-off.

Another parameter of the equation of the cost of fuel is the weight of the payload W_{PL}. It is a part of the total take-off weight. This item of the equation should be corrected with the load factor, that shows an average value of the payload present in each flight. There is the possibility that the aircraft is not full each time and a medium value for the payload mass is required for the estimation. To maximize the profits of the airline company, it is important that the load factor is as higher as possible. It is possible to write that:

$$0 < LF < 1$$

$$W_{PL}^* = LF * W_{PL}$$

$$W_{PL}^* < W_{PL}$$

The load factor LF is considered as a percentage that reduces the value of the maximum payload that can be on board W_{PL}.

All weights in the equations depend on the maximum take-off weight. In fact, this term is fixed and it can not be changed. What it can be modified are the value of its components. Two of the components of the W_{GTO} are the weight of fuel and the weight of payload. It is possible to write that:

$$W_{fT}\ , W_{PL} = f\ (W_{GTO})$$

The performances of the aircraft depend on the quantity of fuel is on board. Considering that the maximum take-off weight is fixed, if the weight of payload increased, the weight of fuel should decrease. This reduces the range, as explained by the reference [45].

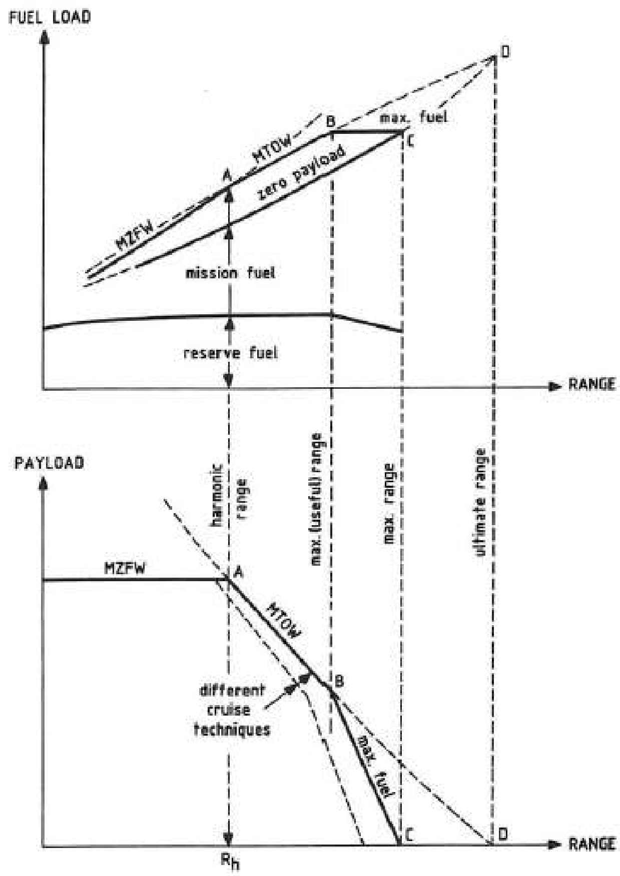


Figure 54: Payload and fuel load envelope versus range [45].

Figure 54 shows the relationship among mission fuel weight, payload weight and range for a certain maximum take-off weight. So, when the payload is zero, the fuel is the highest value as possible. This gives the possibility to reach the maximum range. This solution is not acceptable because the payload (people or cargo) is necessary for profits. If the weight of payload increases, the range is less than the previous case, because the quantity of fuel on board is decreased. The diagrams of Figure 54 depends on the cruise technique, because it is related to the quantity of fuel needed. They are for a subsonic airplane, but it is possible to think that a similar relationship between the weight of payload, the weight of fuel and the range, is present for a hypersonic vehicle for the passengers' transportation.

The last element in the equations of the cost of maintenance is RT, the range of the aircraft. The range is a very important item in the direct operating costs. If it increases, the DOC decreases, as underlined in the reference [46] . In fact, in the NASA equation, the operational range is at denominator of the equation of cost. For the airline companies, it is very interesting to evaluate the direct operating cost per kilometer or per nautical mile, for their cost estimations. To monitor their economic performances the airline companies use two main industry metrics: the Revenue Passenger Kilometers (RPK) and the Available Sets Kilometers (ASK). RPK shows the number ok kilometers flown by paying passengers. ASK is the total of passenger kilometers necessary to determine a specific economical revenue. Both are directly linked with the kilometer traveled by the airplane.

For evaluating the impact of the drivers on the direct operating cost of fuel, it is important to analyze features of a hypersonic aircraft. The following list is developed, which considers the main features of a hypersonic vehicle:

- The fuel
- The propulsion system
- The materials
- The structure
- The systems
- The legislation
- The mission

Table 11 shows the relationships between the new technologies and the elements of the equation in the direct operating cost of fuel. Their effect on the elements of the equation of the DOC of the fuel are now described.

The liquid hydrogen has a different cost than the hydrocarbon fuel. As underlined by the reference [42], if the fuel is LH2 some factors should be taken into account for the evaluation of its price, such as the production country, the production rate and the production techniques. All these factors are a contribute that modify the cost per kilogram of the fuel.

The propulsive system is one of the main drivers of the LAPCAT project. There are various propulsive strategies that can be used to reach the hypersonic speed which are characterized by a specific impulse and a specific fuel consumption (SFC), as it possible to see in Table *11*. The SFC is the fuel necessary to maintain the thrust for a specific period. For this reason, it influences the fuel mass and the maximum take-off weight. The other parameter of the propulsive strategy is the specific impulse. It depends on the thrust and the quantity of fuel. For this reason, it is linked with the fuel weight and the maximum take-off weight. Figure 54 shows the relationship between the fuel mass and the range. In this analysis the range is considered fixed because the mission is the connection between two antipodal cities.

The next element of Table *11* is the materials. Some new composite materials are studied because the hypersonic vehicle should be as lighter as possible but strong enough to face the mechanical and thermal load. The main features of a material are the density and the mechanical properties. They impact on the maximum take-off weight of the aircraft.

Another technological aspect, shown by Table *11*, is the structure. It considers the different shapes that a fuselage can have, the configuration and the presence of stages. Different shapes of fuselages can have different aerodynamic coefficients. They impact on the fuel consumption and the quantity of fuel required for the mission. A similar role is played by the different configurations. An example is the waverider configuration, that permits to increase the lift riding the shock waves of the hypersonic flight. Some hypersonic aircrafts have different stages, that are ejected during the flight. The presence of more than one part, can increased the maximum take-off weight.

Many new systems can be introduced in a hypersonic vehicle. Because it is difficult to precisely know them, in Table *11*it is considered only the aspects of the boil-off and of the weights to evaluate the impact of the new systems on the DOC of fuel. The boil-off of LH2 can be estimated as a percentage of the fuel mass, that is dependent on the maximum take-off weight.

Another aspect of Table *11* is the legislation. New rules are necessary in the case of hypersonic vehicles and they should be considered in the evaluation of the impact on the DOC of fuel. Currently, ICAO prescribe the rules for the evaluation of the reserve of fuel [47]. In the future they will be change, considering the characteristic of the Hypersonic aircrafts.

The lasts aspect of the hypersonic technologies considered in Table *11* is the mission. First of all, the mission profile of a hypersonic aircraft it is not the same of a subsonic jet. Indeed, the vehicles that flies above Mach 1 have some restrictions about the flight over populated area, for the problem of the sonic boom and of the noise. The engines oblige to reach the cruise altitude in steps because they need to flight at a specific altitude; lower that the cruise one, to reach the right thrust level for pushing the vehicle at hypersonic speed. The reference [45] underlines that the quantity of fuel on board depends on both the operational range, but also on the mission profile.

		Cf	**WfT**	**KR**	**LF**	**WPL**	**RT**	**WGTO**
FUEL	**Type**	Cost/ton	ρf					ρf
	Production method	Cost/ton						
	Production rate	Cost/ton						
	Production country	Cost/ton						
PROPULSION	**Propulsion strategy**		sfc - Isp					sfc-Isp
	Operating modes		to - sfc - Isp					to - sfc - Isp
MATERIALS	**New material**							ρm - mech. features
STRUCTURE	**Fuselage type**		cd - cl					l -d -t
	Staging strategy							Wst
	Configuration		cd - cl					
SYSTEMS	**Boil-off**		Kboff					Kboff
	Weight							Wsys
LEGISLATION				#				
MISSION			#					

Table 11: Factors that can influenced the direct operating cost of fuel.

The driver that are not influenced by the new technologies are the range, that is assumed fixed, the load factor and the payload, that is a feature decided in the design phase and it is not modifiable.

The most relevant aspects both under an economic and technological point of view are the fuel and the propulsive strategy. For this reason, they are now analyzed deeper.

Cost of fuel

The cost of fuel is influenced by the following factors:

- The type of fuel;
- The production method;
- The production rate;
- The production country.

The different types of fuel have different physical and chemical properties, that change the cost. In aeronautics, the hydrocarbon fuels are usually used. In the case of hypersonic vehicles, the introduction of liquid hydrogen is required because it is the only fuel that can bring a hypersonic aircraft to reach its performances is liquid hydrogen. It has a specific energy that is three times bigger than the one of the typical aeronautical fuel. It is about 120 MJ/kg. The specific energy of the Jet A is about 43 MJ/kg. The most relevant problem of LH2 is the fact that it is cryogenic and has a low density. Therefore, bigger and heavier tanks are necessary for its storage in the aircraft. This can be observed in the baseline vehicle of the reference [41], having the fuselage almost completely occupied by the tanks for the storage of liquid hydrogen fuel. Special procedures should be studied for the transport and the refueling at the airport, for the fact that is cryogenic and liquid at very low temperatures. In *Table 12*it is possible to see some features of the LH2 and their comparison with the Jet A Fuel.

	Liquid Hydrogen	**Jet A**
Chemical formula	H_2	$C_{11}H_{21}$
Molar mass	2.02 g/mol	170 g/mol
Appearance	Colorless liquid	Straw-colored liquid
Density	70.85 g/L (4.423 lb/cu ft)	775.0-840.0 g/L
Melting point	−259.14 °C (14.01 K; −434.45 °F)	-47 °C (−53 °F; 226 K)
Boiling point	−252.87 °C (20.28 K; −423.17 °F)	176 °C (349 °F; 449 K)

Table 12: Properties of LH2 and comparison with Jet A

The production method, the production rate and the production country are more relevant in the case of liquid hydrogen than in the case of hydrocarbons because the production of LH2 is not so diffuse now. There are many feedstocks to produce LH2. They use natural sources, that can be more or less easily available. The production method is strongly related to the cost of energy, that has a great impact on the final price of fuel. The cost of energy depends on the production country, because the energy price changes considerably between two different countries.

Reference [42] shows that the liquid hydrogen can be produced from different feedstocks and with different techniques:

- From gas, with steam reforming or the partial oxidation
- From oil (fossil or natural oil) by the steam reforming
- From coal by the gasification technology
- From alcohols (ethanol or methanol derived from biomass) by reforming
- From water by electrolysis
- From wood by pyrolysis
- From algae using the photosynthesis

Some of feedstocks are renewable sources and the production method has low impact on the environment.

As mentioned above, the technological processes used for the production of LH2 can be multiple. They can be chemical, biological electrolytic or photolytic.

The choice of the production method of LH2 strongly influences the direct operating cost of the fuel. In the reference [19], it is reported that for the LAPCAT A2 the cost of fuel is about the 83% of the total operating cost, withLH2 produced by the electrolysis of water. The exploitation steam reforming of hydrocarbons would reduce the cost of fuel of a third. Even if it is present this difference of cost, the European Space Agency intend to produce liquid hydrogen by the electrolysis of the water. One of the main reason is the fact of it is environmental friendly, with a low impact, and because it uses a source present in nature without increasing the pollution. The water electrolysis is the process where the water is split in gaseous oxygen and gaseous hydrogen using electricity:

$$H_2O + electricity \rightarrow H_2 + \frac{1}{2}\ O_2$$

The energy required for this process increases slightly with the temperature and the required electricity decreases. When it is possible, a high-temperature process is preferable to avoid consuming electrical energy and increase the price of the process.

As already introduced, another method is the liquefaction. This is one of the most efficient ways to transport hydrogen and it is very cost-effective for large quantity of hydrogen. The today plants for the liquefaction of hydrogen are small and they use reversed helium Bryton and hydrogen Claudes cycles, that are not so efficient. In order to reduce the cost of the production of liquid hydrogen, the total cost of ownership for the liquefaction plants should be reduced and the efficiency should increase with simple process design, optimizing in capital expenditure. The ownership cost of a liquefaction plant includes the plant capital (CAPEX) and the operational (OPEX) expenditures. The CAPEX are the costs linked to the acquisition and the construction of the plant. They are the initial capital. The OPEX are the costs to maintain the production plant operative. They include also the cost of the energy necessary for the liquefaction of the LH2. For reducing the OPEX, the energy efficiency of the process should be increased.

The greatest part of the cost is the CAPEX. To reduce this cost item a simple design process with low risks can be exploited, improving the maintainability and the operability of the plant [48].

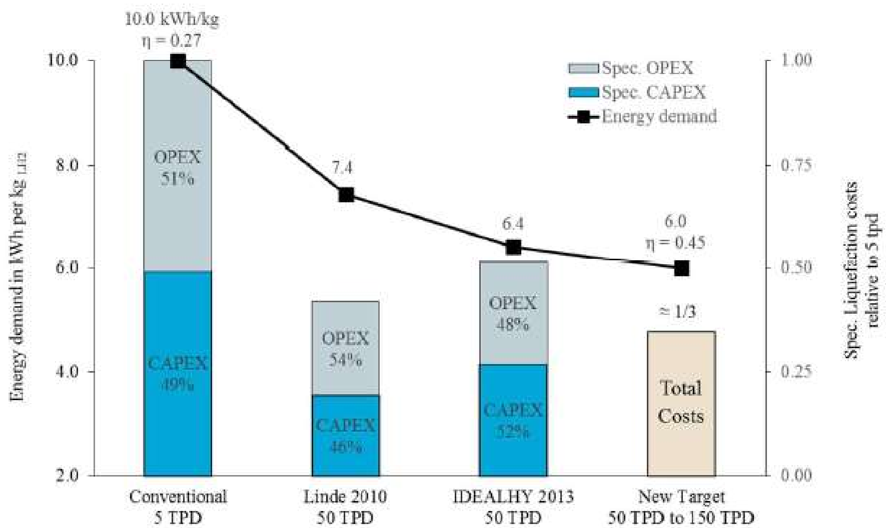


Figure 55: Liquefaction energy demand and costs of conventional and conceptual liquefiers [48] *.*

Another relevant aspect in the production hydrogen is the country where the plant is located. This because the cost of electrical energy is different. The electrical energy is necessary for the production process and it has a great impact on the final price of LH2. In the United States of America, the cost of energy is about a half than Europe, where there are many differences between the countries, as it can be seen in Figure 56. This causes a different price for the fuel, that in Europe is the double than in the USA [49].

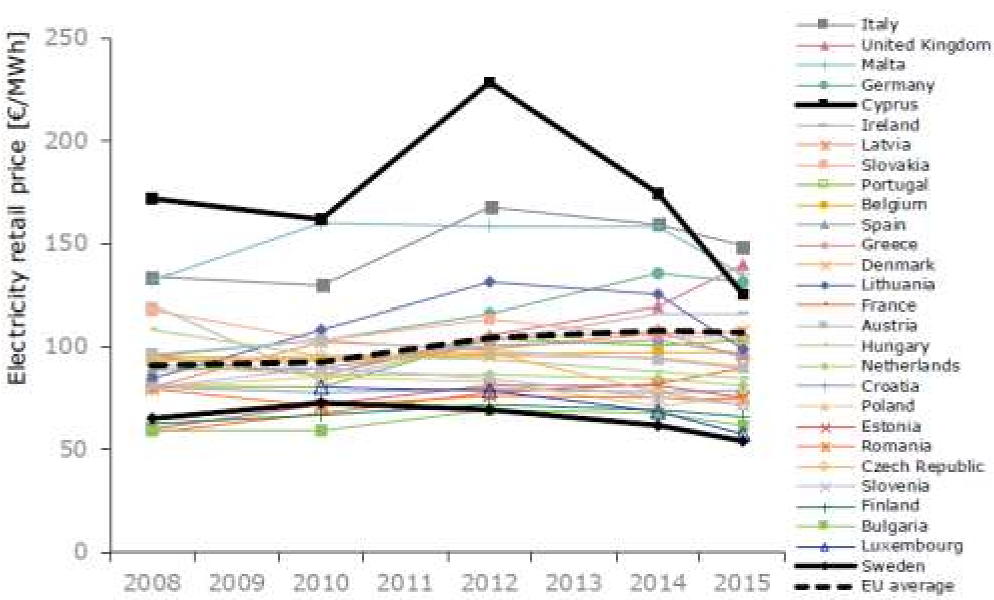


Figure 56: Total electricity price development for industrial consumers [50].

It is difficult to evaluate the cost of hydrogen for the future years, because many elements should be considered, as the economic conditions. A university research gives a method for estimating the price of that fuel for the future years considering different productive scenarios. In this research, it is evaluated the cost of liquid hydrogen considering as production method the electrolysis and the liquefaction, as suggested by ESA. Four different scenarios are evaluated:

1. Today small plant, where the production rate is less than 5 ton/day
2. Today large plant with a production rate of about 10 ton per day
3. Future continuous, with a production rate of 50 ton/day
4. Future off-peak, where the production rate is 200 ton/day

These four different scenarios consider not only the increasing of the production rate, but also the technological improvements will be in the production plants in the future. They are the same of reference [42].

An interesting aspect of this research is the fact of the cost of liquefaction of hydrogen decreases with the increase of the production rate but there is not linear dependency. The relationship between those two elements is logarithmic. Another important characteristic is that the liquefaction cost is assumed to be constant for production rate greater than 100 tons per day. Figure *57* allows to understand the trend of the liquefaction cost of LH2.

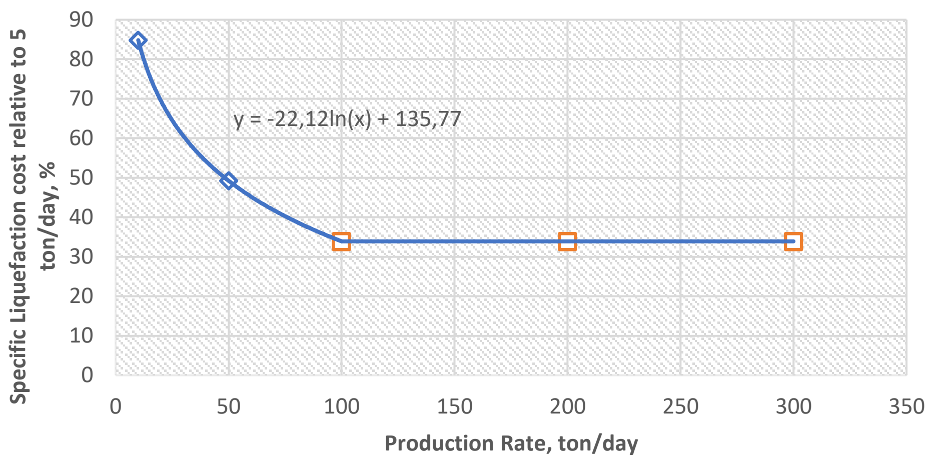


Figure 57: Relationship between liquefaction cost and production rate.

Thanks to a mathematical relationship between the size of the plant and the cost of fuel and the data present in the reference [49], it has been possible to estimate the fuel price for the different scenario both for Europe and for the United States. The cost for the electrolysis present in Table *13* are derived thanks to Figure *53*.

		Europe			USA		
SCENARIO	**ton/day per plant**	**Electr. \$2013/kg**	**Liquef. \$2013/kg**	**Total \$2013/kg**	**Electr. \$2013/kg**	**Liquef. \$2013/kg**	**Total \$2013/kg**
Today Small Plant	2.29	9.83	2.75	12.58	5.20	1.38	6.58
Today Large Plant	10	5.98	2.33	8.32	3.70	1.17	4.86
Future Continuous	50	3.48	1.35	4.83	2.89	0.68	3.57
Future Off-peak	200	2.18	0.92	3.10	2.31	0.46	2.77

Table 13: Cost of liquid hydrogen for different country and different productive scenario (\$2013/kg)

In

Figure *58* it is possible to see the trends of the costs of liquid hydrogen considering the different production countries. The lines of TC (that stand for TransCosts) are derived considering the reference [49], where is present an estimation of the cost of LH2 for different productive scenarios.

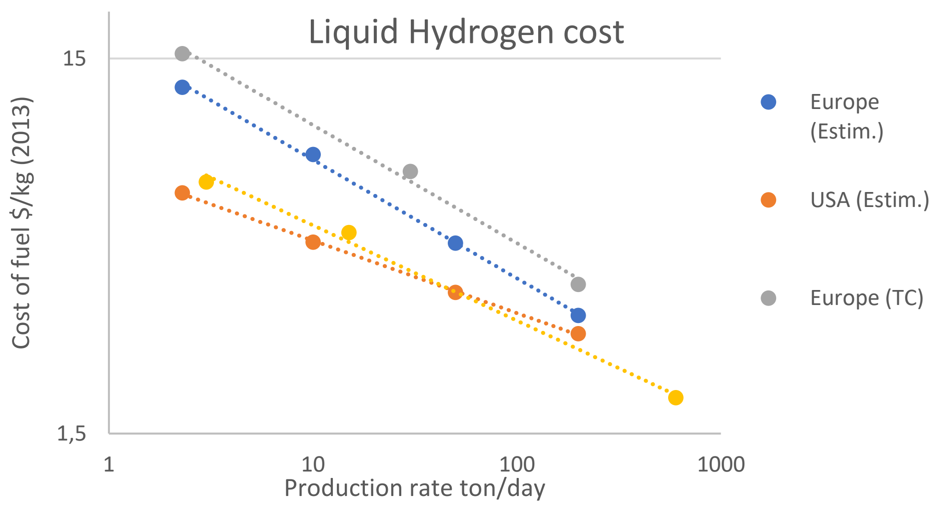


Figure 58: Comparison between the trends of the cost of Liquid Hydrogen

Figure 58It is possible to see that the cost of the LH2 decreases with the growth of production rate.

The cost of fuel is expressed in \$2013 in the reference research. The value can be scaled to the year for which the other costs are required (2017). This is possible using the CPI, consumer price index. It is a numerical factor that considered the changes of price between different years. The CPI is an economic index that allows to evaluate the average prices of consumer goods and services. It can be used to actualize the cost of LH2. Indeed, the ratio between the Consumer Price Index of the estimation and the one of reference year can be multiplied to the cost to actualize it. The cost in the Table *13* are in dollars of 2013. To bring them to the 2017, it has:

$$att = \frac{CPI_{2017}}{CPI_{2013}} = \frac{245.120}{232.957} = 1.052$$

The values of the CPI come from [51].

The price of LH2 for 2017 is in Table 14.

		Europe			USA		
SCENARIO	**ton/day per plant**	**Electr. \$2017/kg**	**Liquef. \$2017/kg**	**Total \$2017/kg**	**Electr. \$2017/kg**	**Liquef. \$2017/kg**	**Total \$2017/kg**
Today Small Plant	2.29	10.34	2.89	13.21	5.46	1.45	6.91
Today Large Plant	10	6.20	2.44	8.73	3.88	1.23	5.10
Future Continuous	50	3.65	1.42	5.07	3.03	0.71	3.75
Future Off-peak	200	2.30	0.97	3.26	2.43	0.48	2.91

Table 14: Cost of liquid hydrogen for different country and different productive scenario (\$2017/kg)

With the mathematical relationships developed in that research, it is possible to estimate the cost of fuel not only for the productive scenarios suggested but also considering different production rates.

The relationships used to evaluate the cost of liquid hydrogen do not consider the possible change of the future economic scenario. Indeed, the industrial production of liquid hydrogen is at the beginning. It needs some decades to make this fuel available at a competitive price and to have an economic return. The first step is the creation of the market for the liquid hydrogen. After that, it is necessary to build new high-level productive plants or to update the existing ones. Moreover, the production techniques should be modified and optimized to meet the market demand. Reference [42] estimates that the stable markets for the LH2 and the profits will be after the 2030.

Propulsive strategy

Another relevant aspect of the new technologies of hypersonic aircraft is the propulsive strategy. As said before, many combinations of engines are possible to reach hypersonic speed. The great challenge is the use of airbreathing engines, as ramjets or turbojets, which are completely reusable. It is possible to use rockets, but their impulse is not adjustable and they are less reusable. In the case of the propulsion systems, the aspects that can impact on the cost drivers are:

- The propulsion strategy
- The operating modes

Figure 59 shows the possible combinations of engines for reaching hypersonic speed. It is interesting to see that the turbojet can be used only for low values of the cruise Mach. To reach hypersonic speed, the ramjets and the scramjets are necessary. Above Mach 8, it is possible to exploit only the rockets. Each type of engines has different performances. In Table *11*, the performances considered are the specific impulse and specific fuel consumption. The first one is linked with the thrust that each engine can generate. The latter depends on the quantity of fuel that is necessary to have a specific thrust. Operating modes are defined by the time of functionating of the engines and by level of thrust and sfc required for that part of the mission. They depend on the configuration of the aircraft, on the propulsive strategy and on the mission planning. In this situation, the LAPCAT A2 uses only the turbojets until it reaches a determined speed then the ramjets are activated to reach the hypersonic speed. In the case of hypersonic aircraft, the possibility to glide in the last phase of the flight it is evaluated. To glide reduces the consumption of the engines. It is possible to associate each phase of the flight to a proper operating mode.

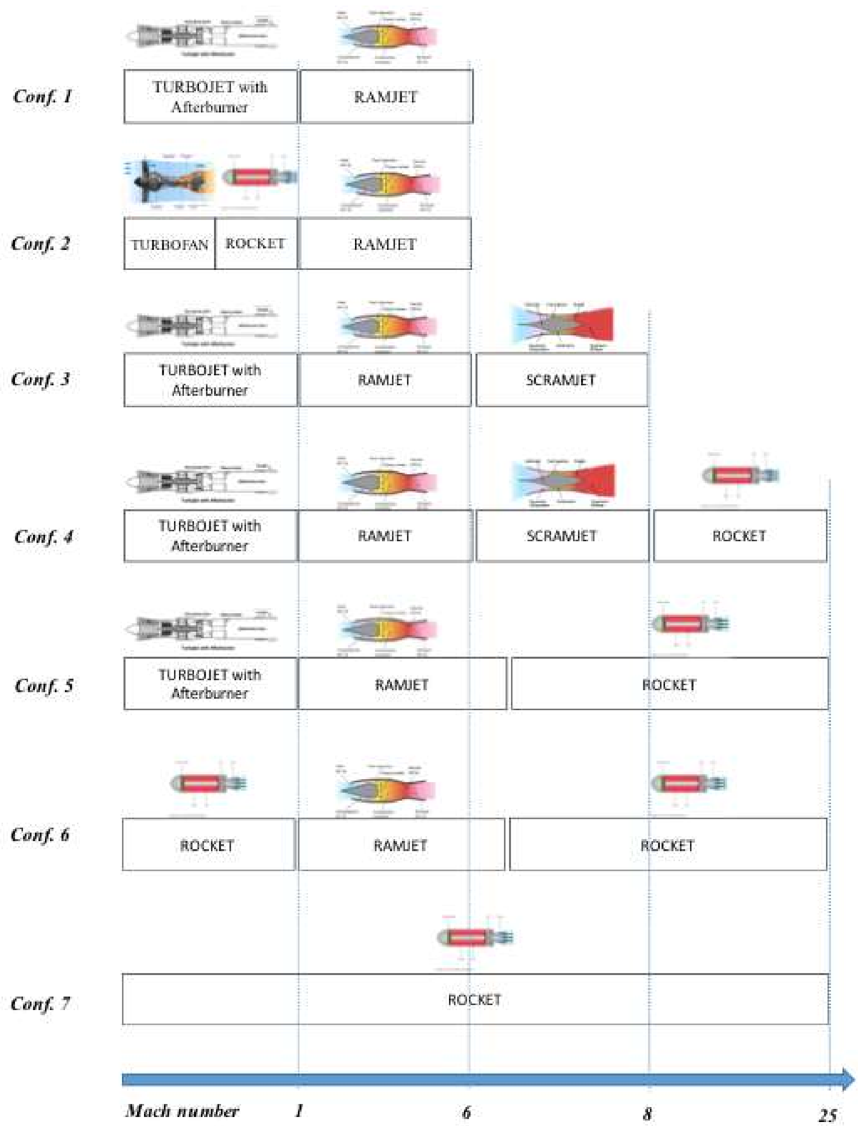


Figure 59: Propulsive strategy for hypersonic flight.

Cost Evaluation Relationship of Direct Operating Cost of Maintenance

The second relationship that is analyzed deeper is the one of the direct operating cost of the maintenance. In the report NASA [41], this equation is divided into six elements. In fact, it is considered the maintenance of the engines and of the airframe (i.e. all the other parts of the aircraft without the engine). For all these terms, it is also evaluated the labor cost, linked with the work of the maintenance workers and t the cost of maintenance materials required for the maintenance activities. The propulsive system for reaching hypersonic speed has turbojets for the flight at low speed and ramjets for fling at high Mach number. Mathematical relationships are developed considering the different features of the two types of engines.

The NASA equation for the maintenance is:

$$\mathrm{DOC_{Maintenance}} = \mathrm{DOC_{M/AF/L}} + \mathrm{DOC_{M/AF/M}} + \mathrm{DOC_{M/TJ/L}} + \mathrm{DOC_{M/TJ/M}} + \mathrm{DOC_{M/RJ/L}} + \mathrm{DOC_{M/RJ/M}}$$

Where:

$M/AF/L$ = airframe and subsystems maintenance labor, excluding engine

$M/AF/M$ = airframe and subsystems maintenance material, excluding engines

$M/TJ/L$ = turbojet maintenance labor

$M/AF/M$ = turbojet maintenance material

$M/RJ/L$ = ramjet maintenance labor

$M/AF/M$ = ramjet maintenance material

The equation the maintenance labor of the airframe and subsystems is:

$$\mathrm{DOC_{M/AF/L}} = \frac{(3.22 + 1.93\ \mathrm{t_f})\left[0.05\ \left(\frac{\mathrm{W_{AF}}}{\mathrm{W_{GTO}}} + \frac{\mathrm{W_{AV}}}{\mathrm{W_{GTO}}}\right) + 0.009\right]\mathrm{M}^{\frac{1}{2}}\,(\mathrm{r_L})}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

where:

$\mathrm{W_{GTO}}$ is the ground take-off weight

$\mathrm{W_{AF}}$ is the weight of the airframe

$\mathrm{W_{AV}}$ is the weight of the avionics

$\mathrm{W_{PL}}$ is the weight of the payload

LF is the load factor

$\mathrm{t_f}$ is the time of flight

M is the cruise Mach.

$\mathrm{r_L}$ is the labor rate (it is the salary of the maintenance worker)

$\mathrm{R_T}$ is the operational range

The equation for the maintenance materials of the airframe and the subsystem is:

$$DOC_{M/AF/M} = \frac{(4.52\ t_f + 9.04)\left(\frac{C_{HST}}{W_{GTO}} - \frac{C_{TJ}}{WGTO} - \frac{C_{RJ}}{W_{GTO}}\right)}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T * 10^3}$$

where:

C_{HST} is the acquisition cost of the aircraft

C_{TJ} is the acquisition cost of turbojets

C_{RJ} is the acquisition cost of ramjets

The NASA relationship for the evaluation of the cost of the maintenance labor of the turbojet is:

$$DOC_{M/TJ/L} = \frac{\left(\frac{T}{W}\right)_{GTO}\ (1 + 0.3\ t_F)\left(\frac{8.60}{T_{TJ} * 10^3} + 0.087\right) r_L\ K_{LTJ}}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

In this equation, there are some parameters that can describe the performances of the turbojet. It has:

$\left(\frac{T}{W}\right)_{GTO}$ the thrust to weight ratio at the take-off

K_{LTJ} is a ratio between the time required to do the maintenance activities on a hypersonic aircraft and the time required for a subsonic jet

The equations of the direct operating costs of maintenance are derived from the ATA model of 1967 [1], where the hypersonic case is not evaluated. The introduction of K_{LTJ} factor gives the possibility to consider the hypersonic case, even if there is not information about the maintenance of hypersonic aircraft in literature.

The NASA equation for the evaluation of the maintenance materials of the turbojet is:

$$DOC_{M/TJ/M} = \frac{\left(\frac{C_{TG}}{W_{GTO}}\right)(0.11\ t_F + 0.029)\ K_{MTJ}}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

Where

K_{MTJ} is a coefficient that compares the frequency of maintenance activities of the traditional turbojet with the ones of hypersonic aircraft.

The equation for the evaluation of the ramjet's maintenance labor is:

$$DOC_{M/RJ/L} = \frac{(1 + t_F)\left(\frac{0.876\ N_{RJ}\left(\frac{L}{D}\right)}{W_{GTO}/\ 10^3} + 0.087\right) r_L\ K_{LRJ}}{\left(\frac{L}{D}\right)(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

Where

K_{LRJ} is a coefficient that compare the maintenance labor of hypersonic ramjet with the engine of a large subsonic jet

The equations for evaluating the cost of the ramjet maintenance are not present in the ATA model of 1967 [1], because it is about subsonic or sonic jets, that do not use the ramjets. They are derived from the turbojet relationships by replacing the terms of the turbojet performances, as the thrust, with the ones that can describe better the performances of the ramjets, as the lift to drag ratio.

The NASA relationship for the evaluation of the cost of the maintenance materials of the ramjet is:

$$DOC_{M/RJ/M} = \frac{\left(\frac{C_{RJ}}{W_{GTO}}\right)(0.036\ t_F + 0.029)\ K_{MRJ}}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

Where:

K_{MRJ} is a coefficient that compares the frequency of maintenance activities for a hypersonic aircraft with the one of large subsonic jet.

As in the case of the CER of the fuel, the equation of maintenance and all its parts are expressed as a cost per ton-mile. All the factors should be expressed with units of measurement of International System. If the English system is used, the numerical factors should be changed.

Before writing an alternative set of equations for the estimation of the direct operating costs some considerations about the factors present in the relationships of maintenance are made.

In all mathematical relationships, it is present the time of flight. it depends on the type of mission and on the range. If the distance between two airports increases, the time necessary to reach them grows too.

All the weights present in the relationships can be considered a fraction of the maximum take-off weight. In fact:

$$W_{GTO} = W_{AF} + W_{AV} + W_{PL} + W_{ft} + W_{eng}$$

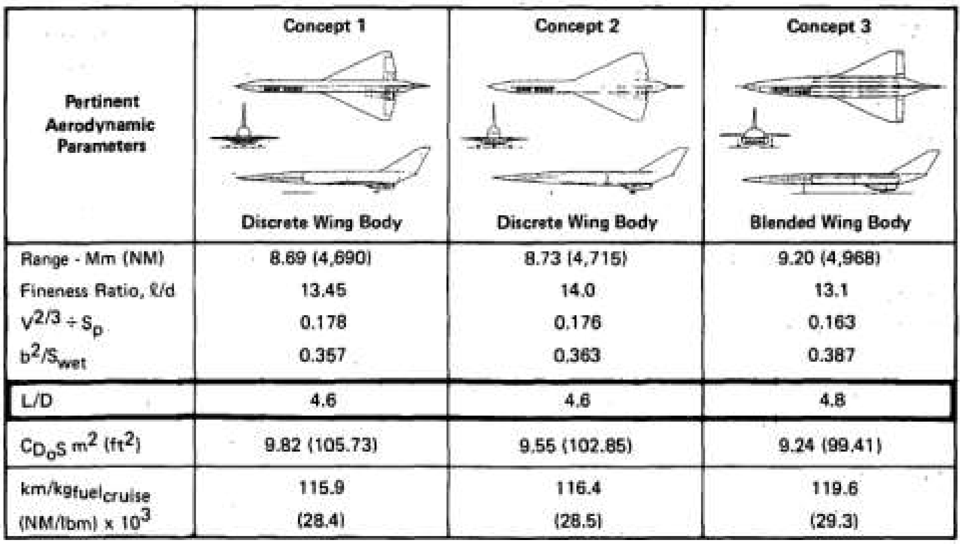
As in the case of the cost evaluation relationship of the fuel, the weight of payload should be corrected with the presence of load factor. For the weight of fuel, the reserve and the boil-off should considered. In the equations of maintenance there is not the weight of the engines, especially the equations for the evaluation of the costs of maintenance material. They are dependent on the acquisition costs. In the relationship of the cost of maintenance material of the airframe, the cruise Mach is present. There is not a linear dependency with the cost and this factor. The Mach number is present with the exponent ½. In all the equations of maintenance material, the labor rate is present. It is the hourly wage of the maintenance worker and the dependencies of the maintenance costs from this factor is clear. If the salary increases, the direct operating cost of maintenance has the same trend. In all the CERs, there is the range at the denominator, because as it is suggested by [46], there is indirect proportionality between the direct operating costs and the range. In all relationships of material, the acquisition costs of the aircraft or of the engines are present. As in the case of the weight, the costs of engines are parts of the total acquisition cost of the vehicle.

As done for the fuel, it is considered which of the new technologies can impact on the direct operating costs of maintenance. These relationships are evaluated in the tables of page 95.

As in the case of the relationships for the direct operating costs of the fuel, the new technological improvements are divide in main categories, they are:

- structure
- propulsion
- materials
- systems
- mission

Considering the case of the structure, the innovations can be the fuselage type, the staging strategy and the configuration. Different fuselage types can have different aerodynamic performances, as it is shown in the Figure 60. In reference [52], it is evaluated the effect of different cross section of the fuselage on the performance of a Mach 6 cruise vehicle. It can be seen that the aerodynamic coefficients strongly depend on the shape of the fuselage. In the equations of maintenance, the aerodynamic performances are expressed by the lift-to-drag ratio, that can be modified by different types of fuselage. Each type of fuselage has different geometrical features that can modify the weight of the airframe and the maximum take-off weight. This driver is present in the relationships of the maintenance of ramjets. The aerodynamic performances are influenced by the configurations too. For hypersonic airplane, it is necessary to design a waverider configuration that can improve the lift coefficients. The new improvements in the structure can modify the weight of the airframe. Probably, a different type of maintenance activity is required and this can change the labor rate of the worker. The presence of more than one stages has impact on the weight of the aircraft that changes during the flight. The maintenance is different because there are more components that should be checked and tested.



Pertinent Aerodynamic Parameters	Concept 1 Discrete Wing Body	Concept 2 Discrete Wing Body	Concept 3 Blended Wing Body
Range - Mm (NM)	8.69 (4,690)	8.73 (4,715)	9.20 (4,968)
Fineness Ratio, ℓ/d	13.45	14.0	13.1
$V^{2/3} \div S_p$	0.178	0.176	0.163
b^2/S_{wet}	0.357	0.363	0.387
L/D	4.6	4.6	4.8
$C_{D_o}S$ m^2 (ft^2)	9.82 (105.73)	9.55 (102.85)	9.24 (99.41)
$km/kg_{fuel_{cruise}}$ (NM/lbm) x 10^3	115.9 (28.4)	116.4 (28.5)	119.6 (29.3)

Figure 60: Aerodynamic characteristics for different fuselage types [52].

The propulsion system is what characterizes a hypersonic aircraft. As in the case of the cost of fuel, what can impact on the terms of equation can be the propulsion strategy, the operating modes of the engines and some structural features as the dimension of the intake. As is the case of the reference vehicle, the LAPCAT A2, the dimension of the aircraft depends a lot from the features of the intakes. They are necessary for giving to the engines the possibility to give a thrust for reaching hypersonic speed. The different propulsion strategies have different performances, as specific fuel consumption or specific impulse. These features can modify the price of the vehicle and the actions necessary for the maintenance. The operating modes can vary the operating time of the engines. This can modify the maintenance activities, that could require more time. This aspect is difficult to evaluate and it is considered in the coefficients typical of the maintenance of ramjet and turbojet, K_{LTJ}, K_{MTJ}, K_{LRJ} and K_{MRJ}.

Other relevant technological factor is the introduction of new materials. These can modify the weight of the vehicle for their different physical and mechanical properties. The maintenance required can be different from the one of traditional jet, especially if it is used composite materials. This can modify the wages of the worker because they need a high level of specialization.

The introduction of new or different subsystems than the ones of a traditional jet can change the weight of the aircraft and the procedures for the maintenance. In the LAPCAT MR2, there is the new system for management of the temperatures. It requires many components as the tube that should be with a great diameter for guarantying the right functioning. This increase the weight of the aircraft and the maintenance activities. In Table 15 it is considered a general contribute for all systems and it not defined which systems are present because the details are unknown.

The mission is considered as a factor that can change the value of the cost of maintenance. The mission of hypersonic aircraft is different than the one of traditional jet. The thermal load is very high and the structure should be strong enough to complete the flight without damages. This increases the acquisition cost of the aircraft, that in the case of the NASA report [41] defines the cost of the materials of the vehicle. The maintenance is not the same of a traditional subsonic jet. A high-level specialization is required and this grows the cost of the labor rate. The coefficients typical of the hypersonic maintenance material should be modified to consider the new requirements.

In Table 15, there are some hash symbols. They show that the new technologies have impact on the drivers but it is not possible to define the factors that can express this relationship. For instance, an unconventional structure modifies the acquisition costs of the aircraft but at this phase of analysis it is difficult to define some coefficients for this connection.

		tF	WAF	WAV	WPL	WGTO	M	rL	LF	RT
STRUCTURE	Fuselage type		Geom. features			Geom. features				
	Staging strategy									
	Configuration									
PROPULSION	Propulsion strategy									
	Operating modes	tf								
	Intake features									
MATERIALS	New materials		ρ_m – mech. features							
SYSTEMS			Wsys			Wsys		#		
MISSION										

		CHST	CTJ	CRJ	(T/W)GTO	Ttj	KLTJ	KMTJ	NRJ	L/D	KLRJ	KMRJ
STRUCTURE	Fuselage type									cl - cd		
	Staging strategy	#										
	Configuration	#								cl - cd		
PROPULSION	Propulsion strategy		#	#	T	T	#	#	#	Isp - T	#	#
	Operating modes											
	Intake features									cdi		
MATERIALS	New materials							#				#
SYSTEMS												
MISSION		#						#				#

Table 15: Relationships with the elements of the equation of the DOC of maintenance

The equation for evaluating the direct operating cost of maintenance has more elements than the others. They are not easy to estimate with the few experimental data available for hypersonic aircraft. The data of maintenance are very hard to find. The coefficients typical of the engines maintenance can be evaluated by extrapolation from the data of subsonic aircraft.

To understand which link there is between the different driver of the equation, it has been used the QFD analysis. QFD means Quality Function Deployment. It is a structured approach to understand the customer needs and put them in an organized plan to produce products that meet those needs [53]. This method is useful to translate the high-level objectives of the customers into low-level objective. The tool, that helps to do this analysis, is a matrix called "House of quality" for its shape. For the right functioning of the method, it is important to understand well the need of the costumers and to develop, as a team, a set of product characteristics and technical requirements that can satisfy those needs. The great advantage of this method is to keep all the information to a manageable level to respond in the best way to the costumers needs.

As it can see in Figure 61, the matrix of QFD method is made by different parts.

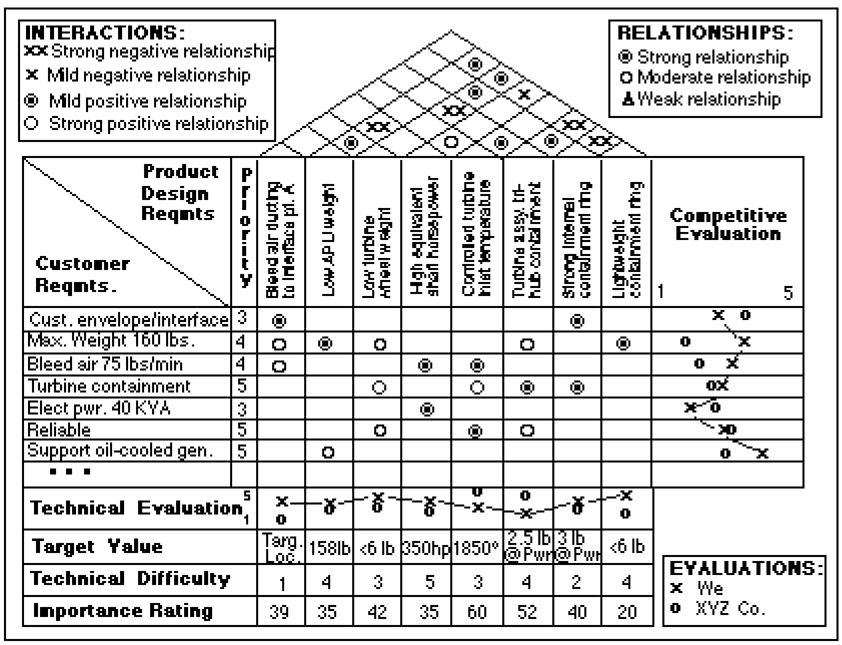


Figure 61: QFD matrix [53].

At the left side of the matrix, the costumers' needs are set in the rows. Usually, they are organized in category and for each of them is defined a level of priority. In the columns there are the product requirements and the technical features that can respond to the costumers' needs. They should be measurable. With a symbolic code, the strong, the medium and the week relationships can be underlined. After that, the importance of each reach requirement suggested can be evaluate translating the symbols in numbers, multiplying the costumer priority rating with the weight factors in each box of the matrix and add the resulting products in each column. Another important aspect is to develop a difficult rating for each product requirement or technical characteristic, considering the technologies available and the manufacturing capability. This give the possibility of doing an analysis of the risks and of the possible difficulties of the project. The roof of the House of Quality gives the possibility to evaluate the interactions between the product requirements and the technical features. The strong positive relationships, the mid positive relationships, the mid negative relationships and the strong negative relationships are again identified using a symbolic code. This gives the possibility identify any contrast or benefit between what is suggested to the costumer.

This last part of the Quality Function Deployment is what is used to identify possible relationships between the element of the cost evaluation relationship for the cost of maintenance.

↗	tF	WAF	WAV	WPL	WGTO	M	rL	LF	RT	CHST	CTJ	CRJ	(T/W)GTO	Ttj	KLTJ	KMTJ	NRJ	(L/D)max	KLRJ	KMRJ
tF					+				+				-			+		+		+
WAF					+					+			-					+		
WAV					+					+			-					+		
WPL					+					+			-					+		
WGTO										+	+	+		+				+		
M										+	+	+	+			+		-		+
rL																				
LF																				
RT										+	+	+			-	-			-	-
CHST											+	+				+				+
CTJ													+	+		+				
CRJ																				+
(T/W)GTO														+				-		
Ttj																				
KLTJ																				
KMTJ																				
NRJ																				
L/D																				
KLRJ																				
KMRJ																				

Table 16: Relationship between the different elements of the CER for the DOC of maintenance

The shape of Table 16 is not the same of the roof of the house of quality but the function is the same. It evaluates how the elements on the rows can impact on the elements in the columns. Only positive or negative relationships are identified. They are symbolized with + and – respectively. Due to the lack of data of hypersonic aircraft, some relationships will be better analyzed. Some pieces of information are taken from subsonic jet reports.

The first term is the time of flight. If it increases, the take-off weight as the same trend because the weight of fuel, that is a part of W_{GTO}, increases. It is necessary more fuel to fly for a longer time. This reduces the thrust-to-weight ratio and increases the lift-to-drag ratio, because between these two terms there is indirect proportionality, as it is underlined in the reference [41]. The different time of flight has effect also in the maintenance coefficients. As it is seen in Figure 62, in the case of subsonic jet, the cost of maintenance decreases, if the time of flight increases. This is due to the fact of the cycle of pressurization for the aircraft are less. This is not the only effect that should be considered in the case of hypersonic flight. In fact, the thermal load is higher and to increase the time of flight could bring a higher deterioration of material, making the coefficients linked to these aspects bigger. The time of flight is directly dependent of the operational range, because if the distance increases, the time of flight has the same trend, if the other features of the aircraft are not modified,

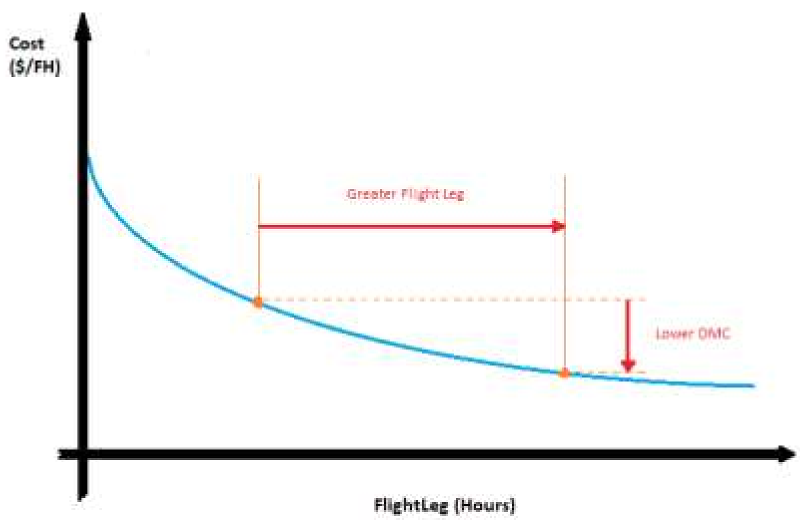


Figure 62: Relationship between the cost of maintenance and the flight time [54].

From Table 16, it is possible to see that all the weights present in the relationships change the maximum take-off weight. This have effect on the aerodynamic and propulsion performance. The cost of maintenance can also vary considering the fact of that more activities are required. The relationship between the increase of the weight and of the direct operating costs is shown in the Figure *63*. There is the same trend for the direct operating cost of maintenance, that is a cost item of the total DOCs

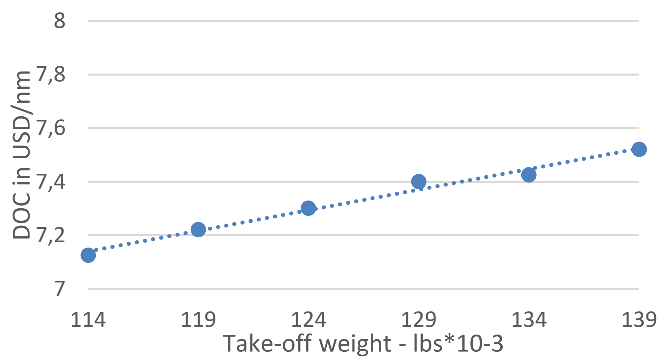


Figure 63: Relationship between the DOC cost and the take-off weight [3].

Thanks to the data of the reference [34], it has been possible to analyze the relationship between the maximum take-off weight and the thrust. The data of the refence comes mainly from subsonic aircrafts, but it is interesting to see that if the maximum take-off weight increases, also the thrust has the same trend.

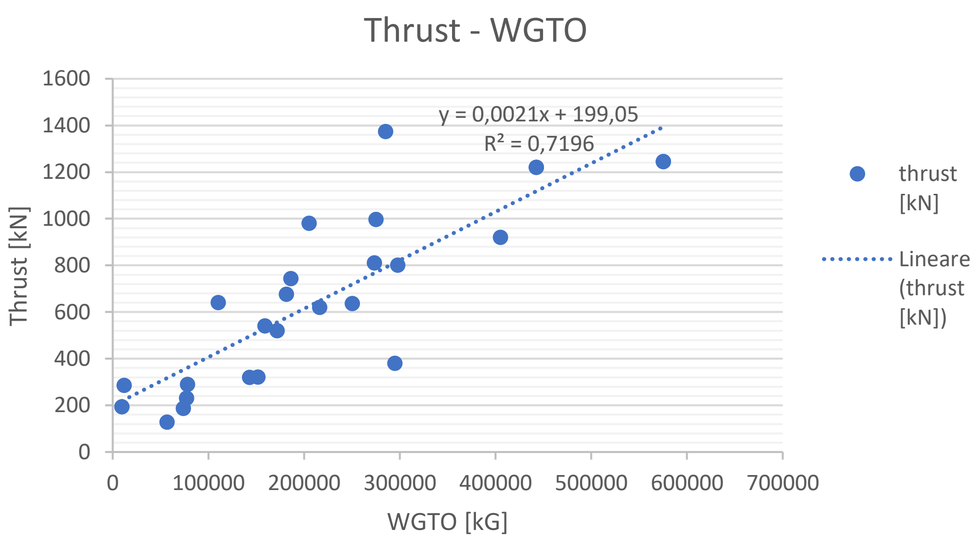


Figure 64: Relationship between the take-off weight and the thrust at the take-off.

The effect of the speed is visible on the cost of vehicle, because it must guarantee high-level performances in a safety way. Increasing the cruise speed, the thermal load grows too. The materials must be strong enough to carry-on this load. This increased the cost of maintenance and in particular the coefficients linked to the maintenance of material. The high speed reduces the aerodynamic features and especially the lift-to-drag ratio, because the drag coefficient increases with the Mach number until it reaches a constant value, as it is shown by *Figure 65*. This effect can be mitigate using typical fuselage configuration, as the waverider, that increases the lift using the shock waves produced by the high-speed flight. This effect of the speed on the aerodynamic performances must be evaluated deeper to see the real impact of the cruise speed on the aerodynamic performances.

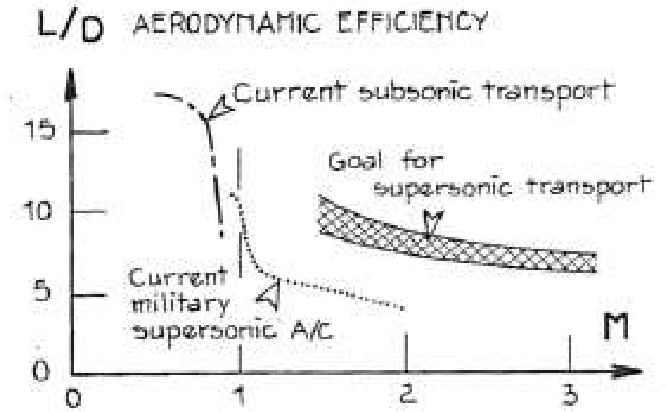


Figure 65: The L/D problem for supersonic flow [55].

The effect of range is important. The direct operating costs tend to decrease with the range or the block distance, as it is shown by *Figure 66*. The same happens for the maintenance costs. If the range decreases, the cost of maintenance is lower because the aircraft have less cycles of pressurization, as underlined by reference [54]. The range has the same effect of the time of flight.

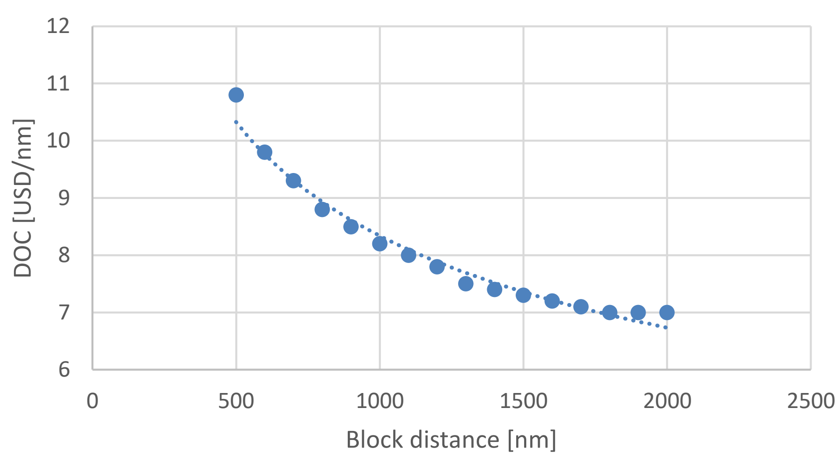


Figure 66: Effect of the block distance on the direct operating costs [3].

As it is shown in reference [41], there is a strong relationship with the acquisition cost and the cost of maintenance. The acquisition price is linked directly to the performance of the aircraft and to its materials. The increase of these two elements makes the coefficients of the maintenance bigger. It is not possible to define which type of relationship is present because there are not data available about the maintenance of hypersonic aircraft. In the case of subsonic vehicle this information is also difficult to find.

Thanks to the data of reference [34], it has been possible to evaluate the effect of the Mach on the specific fuel consumption. This parameter is not present the NASA equation. It is very significant because it is one of the performances of the engines, that are one of the charactering technological improvement of hypersonic aircraft.

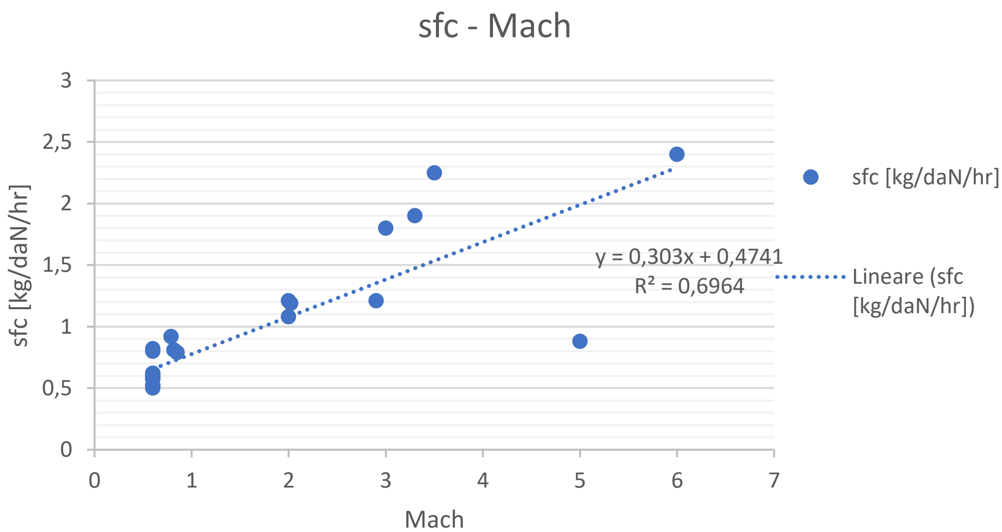


Figure 67: Relationship between the take-off weight and the thrust at the take-off.

The aircrafts of the reference are mainly subsonic. The only hypersonic vehicles are the LAPCAT A2 and the ATLLAS M3. Some sonic airplanes, as the Concorde, are taken into account. It is interesting to see how if the Mach increase, the sfc has the same trend. The specific fuel consumption depends on the fuel flow rate and by the thrust. It is linked with the efficiency of the engine.

Considering what it is shown in the matrix of Table 16, the most considerable elements that can be a great impact on the other variables of the maintenance equations and on the direct operating costs are:

- the maximum take-off weight
- the range of the aircraft
- the acquisition costs
- the propulsive performances

The evaluation of the variation of the direct operating costs with those drivers will be interesting under different points of view. The designers can understand which technological combination can be more cost effective. They can also evaluate how a change in the devices on board can impact on the operating costs. As said in the previous chapters, in the preliminary design phases there is the allocation of the major part of the life cycle costs, but there is also the freedom to change everything in the configuration and production process without many disadvantages in the further phases.

5.4 Introduction of Breguet equation of range in the equation of fuel and maintenance

There is an aeronautical relationship that links the take-off weight, with the range, and propulsive performances. It is the Breguet equation of the range [19]:

$$R = \frac{H}{g}\eta\frac{L}{D}\ln\left[\frac{1}{1-\frac{W_{fT}}{W}}\right] = \frac{V}{g\,sfc}\frac{L}{D}\ln\left[\frac{1}{1-\frac{W_{fT}}{W}}\right]$$

Where:

R : Range [m]

H: fuel energy content [J/kg]

g: gravity constant [m/s^2]

η: overall installed engine efficiency

sfc: specific fuel consumption [kg/s/N]

V: flight velocity [m/s]

W: total take-off mass [kg]

W_{fT}: fuel mass [kg]

It is a simplified relationship that links the range of the cruise with some of aircraft performances and features. In particular it is interesting the presence of the fuel mass and of the specific fuel consumption.

As underlined in the previous section, the range is an important parameter in the evaluation of the direct operating costs. It is a very significant element in the NASA equations, in fact it is present in the relationship of the cost of fuel and in the relationship of maintenance. Those CERs are considered the most important under a technological point of view.

The Breguet equation of range is exploited to rewrite the equation of fuel and maintenance for evaluating the effect of the engines performances on the direct operating costs. The engine strategy is what characterized a hypersonic vehicle, because it gives the possibility to reach the speed required.

Thanks to the Breguet equation, it is possible to evaluate also the effect of the aerodynamic and propulsive performances on the direct operating costs. Those terms in the NASA equation are less evident, but they are distinguishing for a hypersonic vehicle

The NASA equation [41] for the evaluation of the DOC of fuel is:

$$\mathrm{DOC_{Fuel}} = \frac{1460\ \mathrm{C_f}\left(\frac{\mathrm{W_{fT}}}{\mathrm{W_{GTO}}}\right)(1-\mathrm{K_R})}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

Where:

$\mathrm{W_{fT}}$ is weight of fuel

$\mathrm{W_{PL}}$is the weight of the payload

$\mathrm{W_{GTO}}$ is the maximum take-off weight

$\mathrm{C_f}$ is the unitary cost of fuel.

$\mathrm{R_T}$ is the range of the vehicle

$\mathrm{K_R}$ is the reserve of fuel

Using the Breguet relationship, it becomes:

$$\mathrm{DOC_{Fuel}} = \frac{1460\ \mathrm{C_f}\left(\frac{\mathrm{W_{fT}}}{\mathrm{W_{GTO}}}\right)(1-\mathrm{K_R})}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\frac{V}{g\,sfc}\frac{L}{D}\ \ln\left[\frac{1}{1-\frac{W_{fT}}{W}}\right]*10^{-3}}$$

The Breguet equations is multiplied by 10^{-3}, because in the NASA equation the range must be in kilometers.

As said before, one of the important element of the Breguet equation is the presence of the fuel weight. It is possible to obtain the ratio between the fuel weight and the maximum take-off weigh from the range relationship:

$$R = \frac{V}{g*sfc}\left(\frac{L}{D}\right)\ln\left[\frac{1}{1-\frac{W_{fT}}{W_{GTO}}}\right] \rightarrow \frac{W_{fT}}{W_{GTO}} = 1 - \frac{1}{\exp\left(\frac{R*g*sfc}{V*\left(\frac{L}{D}\right)}\right)}$$

Using this term in the DOC fuel, it has:

$$\mathrm{DOC_{Fuel}} = \frac{1460\ \mathrm{C_f}\left(1 - \dfrac{1}{\exp\left(\dfrac{R * g * sfc}{V * \left(\dfrac{L}{D}\right)}\right)}\right)(1 - \mathrm{K_R})}{(\mathrm{LF})\ \left(\dfrac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

It is possible to exploit the equation of range of Breguet also in the equation of maintenance. The NASA equation of maintenance have the range at the denominator. In the case of the DOC of the maintenance labor of ramjet, it is possible to use the Breguet equation for obtain the aerodynamic efficiency.

The NASA equations for the maintenance of the airframe are:

$$\mathrm{DOC_{M/AF/L}} = \frac{(3.22 + 1.93\ \mathrm{t_f})\left[0.05\ \left(\dfrac{\mathrm{W_{AF}}}{\mathrm{W_{GTO}}} + \dfrac{\mathrm{W_{AV}}}{\mathrm{W_{GTO}}}\right) + \mathrm{coef}\right]\mathrm{M}^{\frac{1}{2}}\ (\mathrm{r_L})}{(\mathrm{LF})\left(\dfrac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

$$\mathrm{DOC_{M/AF/M}} = \frac{(4.52\ \mathrm{t_f} + 9.04)\left(\dfrac{\mathrm{C_{HST}}}{\mathrm{W_{GTO}}} - \dfrac{\mathrm{C_{TJ}}}{\mathrm{WGTO}} - \dfrac{\mathrm{C_{RJ}}}{\mathrm{W_{GTO}}}\right)}{(\mathrm{LF})\left(\dfrac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T} * 10^3}$$

where:

$\mathrm{W_{GTO}}$ is the ground take-off weight

$\mathrm{W_{AF}}$ is the weight of the airframe

$\mathrm{W_{AV}}$ is the weight of the avionics

$\mathrm{W_{PL}}$ is the weight of the payload

LF is the load factor

$\mathrm{t_f}$ is the time of flight

M is the cruise Mach.

$\mathrm{r_L}$ is the labor rate (it is the salary of the maintenance worker)

$\mathrm{R_T}$ is the operational range

$\mathrm{C_{HST}}$ is the acquisition cost of the aircraft

$\mathrm{C_{TJ}}$ is the acquisition cost of turbojets

$\mathrm{C_{RJ}}$ is the acquisition cost of ramjets coef is a coefficient that depends on the weight of the airframe and avionics and the maximum take-off weight.

Exploiting the Breguet relationship of the range for the equation of maintenance, the maintenance airframe labor excluding the engines becomes:

$$\mathrm{DOC_{M/AF/L}} = \frac{(3.22 + 1.93\ \mathrm{t_f})\left[0.05\ \left(\frac{\mathrm{W_{AF}}}{\mathrm{W_{GTO}}} + \frac{\mathrm{W_{AV}}}{\mathrm{W_{GTO}}}\right) + \mathrm{coef}\right] \mathrm{M}^{\frac{1}{2}}\ (\mathrm{r_L})}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\frac{V}{g\ sfc}\frac{L}{D}\ \ln\left[\frac{1}{1 - \frac{W_{fT}}{W}}\right] * 10^{-3}}$$

The presence of the factor 10^{-3} at the denominator depends on the fact that the Range in the Breguet equation is meter and the equation required kilometers.

Also in the equation of the maintenance airframe material the range is present. It has:

$$\mathrm{DOC_{M/AF/M}} = \frac{(4.52\ \mathrm{t_f} + 9.04)\left(\frac{\mathrm{C_{HST}}}{\mathrm{W_{GTO}}} - \frac{\mathrm{C_{TJ}}}{\mathrm{WGTO}} - \frac{\mathrm{C_{RJ}}}{\mathrm{W_{GTO}}}\right)}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\frac{V}{g\ sfc}\frac{L}{D}\ \ln\left[\frac{1}{1 - \frac{W_{fT}}{W}}\right]}$$

The NASA equations for the maintenance of the turbojet are:

$$\mathrm{DOC_{M/TJ/L}} = \frac{\left(\frac{\mathrm{T}}{\mathrm{W}}\right)_{\mathrm{GTO}}\ (1 + 0.3\ \mathrm{t_F})\left(\frac{8.60}{\mathrm{T_{TJ}} * 10^3} + 0.087\right)\mathrm{r_L}\ \mathrm{K_{LTJ}}}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

$$\mathrm{DOC_{M/TJ/M}} = \frac{\left(\frac{\mathrm{C_{TG}}}{\mathrm{W_{GTO}}}\right)(0.11\ \mathrm{t_F} + 0.029)\ \mathrm{K_{MTJ}}}{(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

Where:

$\left(\frac{\mathrm{T}}{\mathrm{W}}\right)_{\mathrm{GTO}}$ the thrust to weight ratio at the take-off

K_{LTJ} is a ratio between the time required to do the maintenance activities on a hypersonic aircraft and the time required for a subsonic jet.

$\mathrm{K_{MTJ}}$ is a coefficient that compares the frequency of maintenance activities of the traditional turbojet with the ones of hypersonic aircraft.

The equation of the maintenance labor of turbojet can be rewritten as:

$$DOC_{M/TJ/L} = \frac{\left(\frac{T}{W}\right)_{GTO} (1 + O.3t_F) \left(\frac{\frac{8.6}{T_{TJ}}}{10^3} + O.087 \right) r_L K_{LTJ}}{(LF) \left(\frac{W_{PL}}{W_{GTO}}\right) \frac{V}{g\ sfc} \frac{L}{D} \ln\left[\frac{1}{1 - \frac{W_{fT}}{W}}\right] * 10^{-3}}$$

The equation of the cost of the material for the turbojet maintenance becomes:

$$\mathrm{DOC_{M/TJ/M}} = \frac{(4.52\ \mathrm{t_f} + 9.04) \left(\frac{\mathrm{C_{HST}}}{\mathrm{W_{GTO}}} - \frac{\mathrm{C_{TJ}}}{\mathrm{WGTO}} - \frac{\mathrm{C_{RJ}}}{\mathrm{W_{GTO}}}\right)}{(\mathrm{LF}) \left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right) \frac{V}{g\ sfc} \frac{L}{D} \ln\left[\frac{1}{1 - \frac{W_{fT}}{W}}\right] * 10^{-3}}$$

The NASA equations for the maintenance of the ramjet are:

$$\mathrm{DOC_{M/RJ/L}} = \frac{(1 + \mathrm{t_F}) \left(\frac{0.876\ \mathrm{N_{RJ}} \left(\frac{\mathrm{L}}{\mathrm{D}}\right)}{\mathrm{W_{GTO}}/\ 10^3} + 0.087 \right) \mathrm{r_L\ K_{LRJ}}}{\left(\frac{\mathrm{L}}{\mathrm{D}}\right) (\mathrm{LF}) \left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right) \mathrm{R_T}}$$

$$\mathrm{DOC_{M/RJ/M}} = \frac{\left(\frac{\mathrm{C_{RG}}}{\mathrm{W_{GTO}}}\right) (0.036\ \mathrm{t_F} + 0.029)\ \mathrm{K_{MRJ}}}{(\mathrm{LF}) \left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right) \mathrm{R_T}}$$

Where:

$\mathrm{K_{LRJ}}$ is a coefficient that compare the maintenance labor of hypersonic ramjet with the engine of a large subsonic jet

$\mathrm{K_{MRJ}}$ is a coefficient that compares the frequency of maintenance activities for a hypersonic aircraft with the one of large subsonic jet

Substituting the range at the dominator of the equation of the maintenance labor of the ramjet, it has:

$$\mathrm{DOC_{M/RJ/L}} = \frac{(1+\mathrm{t_F})\left(\frac{0.876\ \mathrm{N_{RJ}}\ \left(\frac{\mathrm{L}}{\mathrm{D}}\right)}{\mathrm{W_{GTO}}/\ 10^3} + 0.087\right)\mathrm{r_L}\ \mathrm{K_{LRJ}}}{\left(\frac{\mathrm{L}}{\mathrm{D}}\right)(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\frac{V}{g\ sfc}\frac{L}{D}\ \ln\left[\frac{1}{1-\frac{W_{fT}}{W}}\right] * 10^{-3}}$$

As said before, from the Breguet equation is possible to obtain the aerodynamic efficiency:

$$R = \frac{V}{g * sfc}\left(\frac{L}{D}\right)\ln\left[\frac{1}{1-\frac{W_{fT}}{W_{GTO}}}\right] \rightarrow \frac{L}{D} = \frac{R * g * sfc}{V * \ln\left[\frac{1}{1-\frac{W_{fT}}{W_{GTO}}}\right]}$$

Using the last formula of the lift-to-drag ratio in the equation of the maintenance labor of the ramjet, it has:

$$\mathrm{DOC_{M/RJ/L}} = \frac{(1+\mathrm{t_F})\left(\frac{0.876\ \mathrm{N_{RJ}}\left(\frac{R * g * sfc}{V * \ln\left[\frac{1}{1-\frac{W_{fT}}{W_{GTO}}}\right]}\right)}{\mathrm{W_{GTO}}/\ 10^3} + 0.087\right)\mathrm{r_L}\ \mathrm{K_{LRJ}}}{\left(\frac{R * g * sfc}{V * \ln\left[\frac{1}{1-\frac{W_{fT}}{W_{GTO}}}\right]}\right)(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\mathrm{R_T}}$$

The last equation of the maintenance is about the evaluation of the material maintenance cost of the ramjet. Using the Breguet equation of the range, it becomes:

$$\mathrm{DOC_{M/RJ/L}} = \frac{(1+\mathrm{t_F})\left(\frac{0.876\ \mathrm{N_{RJ}}\ \left(\frac{\mathrm{L}}{\mathrm{D}}\right)}{\mathrm{W_{GTO}}/\ 10^3} + 0.087\right)\mathrm{r_L}\ \mathrm{K_{LRJ}}}{\left(\frac{\mathrm{L}}{\mathrm{D}}\right)(\mathrm{LF})\left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right)\frac{V}{g\ sfc}\frac{L}{D}\ \ln\left[\frac{1}{1-\frac{W_{fT}}{W}}\right] * 10^{-3}}$$

These equations modified using the Breguet equation have been applied to the refence vehicle. In the chapter seven, there is the comparison between the results obtained using the NASA method [41] and these rewritten equations. The values obtained are not the same but they are comparable. This is due to the fact of that the Breguet formula evaluates only the cruise range that is different from the total range of the reference vehicle. The Breguet formulas is an approximated formulation. It is assumed that all the terms are constant. This is not true because the lift-to-drag ratio and the specific fuel consumption change during the flight.

5.5 Acquisition costs equations in the relationship of insurance and depreciation

In the equation of the insurance and depreciation, the operational range is not present. For evaluating the impact of new technologies on those direct operating cost, it is possible to use some relationships present in the reference [41] for the estimation of the acquisition cost.

According to the reference [41], the acquisition cost is the sum of the cost of the airframe, of engine and avionics:

$$\frac{C_{HST}}{W_{GTO}} = \frac{C_{AF}}{W_{GTO}} + \frac{C_{TJ}}{W_{GTO}} + \frac{C_{RJ}}{W_{GTO}} + \frac{C_{AV}}{W_{GTO}}$$

The costs are divided by the take-off weight because in this way they appear in the cost estimation relationships.

The cost of the airframe per kilogram is:

$$\frac{C_{AF}}{W_{GTO}} = \frac{855\ W_{AF}^{0.68}\ M^2}{W_{GTO}}$$

Where:

W_{AF} is the weight of the airframe

M is the cruise Mach

The acquisition cost of the turbojet is:

$$\frac{C_{TJ}}{W_{GTO}} = 6300\ N_{TJ}^{-0.15}\ T_{TJ}^{-0.33}\ \left(\frac{T}{w}\right)_{GTO}$$

Where:

N_{TJ} is the number of turbojets

T_{TJ} is he thrust of the turbojet

$\left(\frac{T}{W}\right)_{GTO}$ is the thrust to weight ratio at the take-off

The cost of the ramjet is:

$$\frac{C_{RJ}}{W_{GTO}} = \frac{33900\ A_C^{0.9}\ M^2}{W_{GTO}}$$

Where :

A_C is the total ramjet cowl area

The cost of avionic per kilogram is:

$$\frac{C_{AV}}{W_{GTO}} = \frac{2760\ W_{AV}}{W_{GTO}}$$

Where

W_{AV} is the weight of avionics

All the costs are in $\frac{\$}{kg}$ and all the data must be in International System of measurement.

It is interesting to see that this acquisition costs depends on the performances and the features of the aircraft, as the weights or thrust. Those factors can change, if there are different technologies on board.

It is possible to rewrite the equation of insurance and of the depreciation using the previous relationships. This gives the possibility to evaluate the technological impact also on these two cost equations, that do depend on the operational range.

The NASA equation of insurance is:

$$\mathrm{DOC_{Insurance}} = \frac{(\mathrm{IR})\ \left(\frac{\mathrm{C_{HST}}}{\mathrm{W_{GTO}}}\right)}{0.725\ (\mathrm{LF})\ \left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right) \mathrm{M}\ \left(\frac{\mathrm{V_B}}{\mathrm{V_{CR}}}\right) \mathrm{U}}$$

Where:

IR is the insurance rate

$\mathrm{V_B}/\mathrm{V_{CR}}$ is the ratio between the block speed and the cruise speed

U is the utilization of the aircraft

Using the relationship for the evaluation of the acquisition cost of the aircraft, it has:

$$\mathrm{DOC_{Insurance}} = \frac{(\mathrm{IR})\ \left(\frac{855\ W_{AF}^{0.68}\ M^2}{W_{GTO}} + 6300\ N_{TJ}^{-0.15}\ T_{TJ}^{-0.33}\ \left(\frac{T}{W}\right)_{GTO} + \frac{33900\ A_C^{0.9}\ M^2}{W_{GTO}} + \frac{2760\ W_{AV}}{W_{GTO}}\right)}{0.725\ (\mathrm{LF})\ \left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right) \mathrm{M}\ \left(\frac{\mathrm{V_B}}{\mathrm{V_{CR}}}\right) \mathrm{U}}$$

The NASA equation of depreciation is:

$$DOC_{Depreciation} = \frac{1.1\left(\frac{C_{HST}}{W_{GTO}}\right) + 0.3\left(\frac{C_{TJ}}{W_{GTO}} + \frac{C_{RJ}}{W_{GTO}}\right)}{0.725\ (\mathrm{LF})\ \left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right) \mathrm{M}\ \left(\frac{\mathrm{V_B}}{\mathrm{V_{CR}}}\right) \mathrm{U}}$$

Using the previous relationships, it becomes:

$$DOC_{Depreciation} = \frac{1.1\left(\frac{855\ W_{AF}^{0.68}\ M^2}{W_{GTO}} + 6300\ N_{TJ}^{-0.15}\ T_{TJ}^{-0.33}\ \left(\frac{T}{w}\right)_{GTO} + \frac{33900\ A_C^{0.9}\ M^2}{W_{GTO}} + \frac{2760\ W_{AV}}{W_{GTO}}\right) + 0.3\left(6300\ N_{TJ}^{-0.15}\ T_{TJ}^{-0.33}\ \left(\frac{T}{w}\right)_{GTO} + \frac{33900\ A_C^{0.9}\ M^2}{W_{GTO}}\right)}{0.725\ (\mathrm{LF})\ \left(\frac{\mathrm{W_{PL}}}{\mathrm{W_{GTO}}}\right) \mathrm{M} \left(\frac{\mathrm{V_B}}{\mathrm{V_{CR}}}\right) \mathrm{U}}$$

These two rewritten expressions will be used for the evaluation of the direct operating cost of the reference vehicle, because the acquisition costs of the LAPCAT A2 are not available. Some data about the cost estimation of the reference aircraft [19] are present in the reference about the cost estimation of the reference aircraft [19]. For the DOCs estimation it is assumed the production of 200 units, because further studies show that the production target is 200 vehicles. The value of reference [19] are related to the production of 100 aircrafts, so they cannot be used. A change in the number of airplanes built modifies both the production costs and the acquisition price. In those reference there are not any data about the acquisition price of the engines, of the airframe or of the avionics. This information is necessary for the application of the NASA CERs for the evaluation of direct operating costs of hypersonic point-to-point vehicle. Some studies show that the acquisition costs evaluated with the NASA formulation can be considered reliable.

6. MATLAB tool

The equations developed for the costs estimations have been implemented in an ad-hoc built-in tool developed in MATLAB. In particular, the estimation of DOC will be embedded in a more complex tool for LCC estimation of hypersonic transportation systems.

MATLAB has been selected as platform for developing of the program for compatibility reasons mainly, but also for the possibility of creating graphical user interfaces (GUIs) to enter the data and analyze the results. A non-expert user is guided through-out the cost estimation thanks to clear instructions suggested by the interfaces. The user does not act on code written by another person with the possibility to do errors or to modify in a wrong way parts of that code. Another important aspect is possibility to save inputs and the results on Excel files. Once the worksheet is created, the user can modify it, changing the data entered previously in the program. The data present in the worksheet can be reloaded designing specific import functions. The great advantage of using an Excel file is related to import/export activities, allowing external pre/post processing of data with other external software. In the worksheet, the data organized in table and divided according to the subdivision made in the program.

In the first section of this chapter, there is a description of the logic laying behind the tool structure.

After that, there is a detailed analysis of each part of the program. The organization of each interfaces explained with a specific focus on each input to be inserted.

6.1 Development and description of the tool

Various prototypes have been developed before reaching the final configuration of the program. The last version of the tool is the more complete. Indeed, once it is completely developed, it gives the possibility to evaluate all life cycle costs of hypersonic aircraft and to evaluate the impact of the new technologies on the LCCs. Now, it is possible only the evaluation of the DOCs of hypersonic point-to-point vehicle, thanks to the NASA modified ATA CERs [41]. Compared to the previous version of the program, the last one organizes the input required to the user in a more clearly way to help him.

In the Figure 68, there is the organization's scheme of the last program developed.

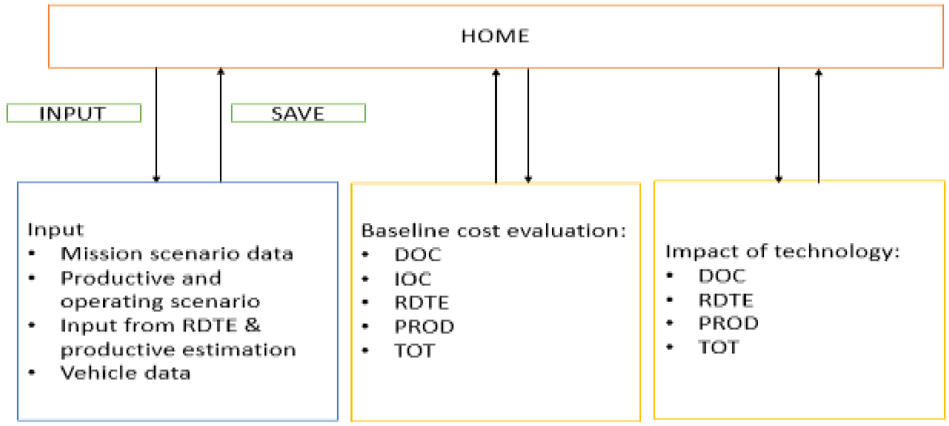


Figure 68: Chart of the final MATLAB tool for the cost evaluation of a Cruise Air Vehicle

The tool is developed using MATLAB version R2016b – educational edition. The Microsoft Excel version is the 2016. The hardware is a laptop with Intel Core i7.

In the first screen, called Home, the user can access to the different part of the tool.

The "Input" pushbutton opens the section dedicated to the entering of the input data following these categorization:

- Mission scenario data, describing the major features related to the mission profile such as the time of flight or cruise Mach.
- Productive and operating scenario data, where the user may enter data relative of the economic and the operative scenario, as the type of fuel or the load factor for the flight.
- Input from RDTE & productive estimation, where there the user may import/insert data coming from RDTE & Production costs estimation of the vehicle and of main components, such as the engines.
- Vehicle data collecting technical features of vehicle and its performances.

Dedicated Input and Save buttons are used to pass from one window to another one. They have a strategic role in data saving, as well as import/export management

From the Home screen, the user may access to two sections:

1. Baseline cost evaluation, where the overall life cycle costs of the Cruise Air Vehicle (CAV) can be estimated. Different pushbuttons allow accessing the results of the cost estimation and graphics to evaluate trends. Of course, both partial results and complete results may be access.
2. Impact of technology, where it is possible to evaluate how a change in the technologies on-board impacts on the costs. The groups of costs considered are the direct operating costs, the costs of RDTE phase and the acquisition costs

In the framework of the activities for the thesis, only the section for the DOC evaluation of the baseline has been developed in detail. In particular, the equations of the NASA model [41] have been implemented. In fact, in the case of the LAPCAT A2, they give the values of costs that are consistent with the first estimations done in other studies, as [19]. When other models for the evaluation of the life cycle costs are available and validated, it will be possible to complete all the other parts for the estimation of life cycle costs and for the evaluation of the impact of the new technologies on the costs of the aircraft.

6.2 Description of the tool

In this second section of the chapter, there is the description of the tool for the evaluation of the direct operating costs. The interfaces of the program are shown and described with a brief explanation of the different inputs required to the users. There are also some suggestions for the correct use of the program.

In *Figure 69*, there is the first screen of the program. It has been called Home.

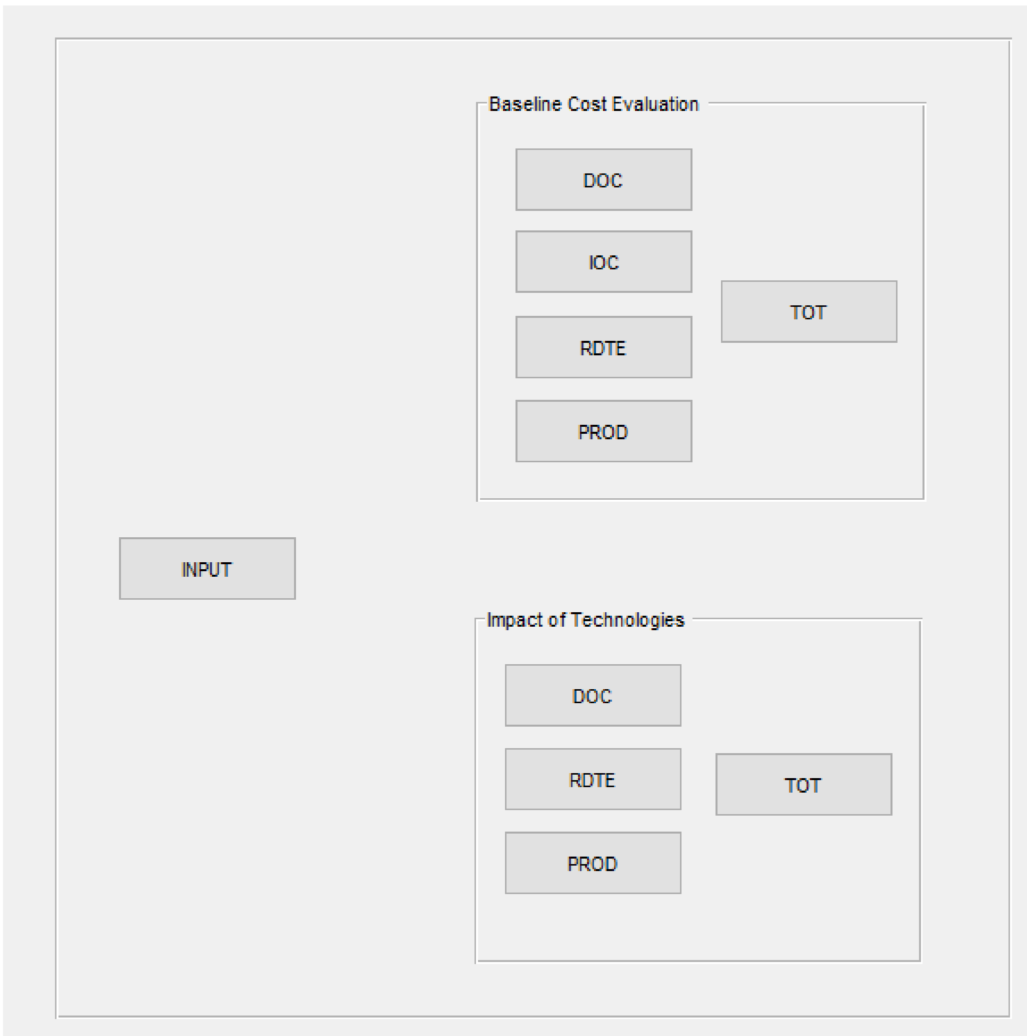


Figure 69: Home screen of MATLAB tool for the Cruise Air Vehicle cost evaluation.

In the left side of the interface, there is the button INPUT, opening a new screen where are present some sections for entering the data of the cruise air vehicle. At the right side there are nine pushbuttons divided in two sections. The first one is for the evaluation of the life cycle cost of the baseline, the second one is for evaluating the impact of the changes of technologies on different type of costs.

The life cycle costs are split into:

- Direct Operating Costs, DOC
- Indirect Operating Costs, IOC
- Research, development, test and evaluation costs, RDTE
- Productive costs, PROD

Of course, it is also possible evaluate the total cost of the aircraft using the pushbutton TOT.

In the case of the evaluation of the impact of technological changes on the Direct Operating Costs, RDTE costs and Productive costs.

Only the part about the DOCs baseline estimation is developed in detail.

Pushing the button INPUT, the screen of the input will be opened.

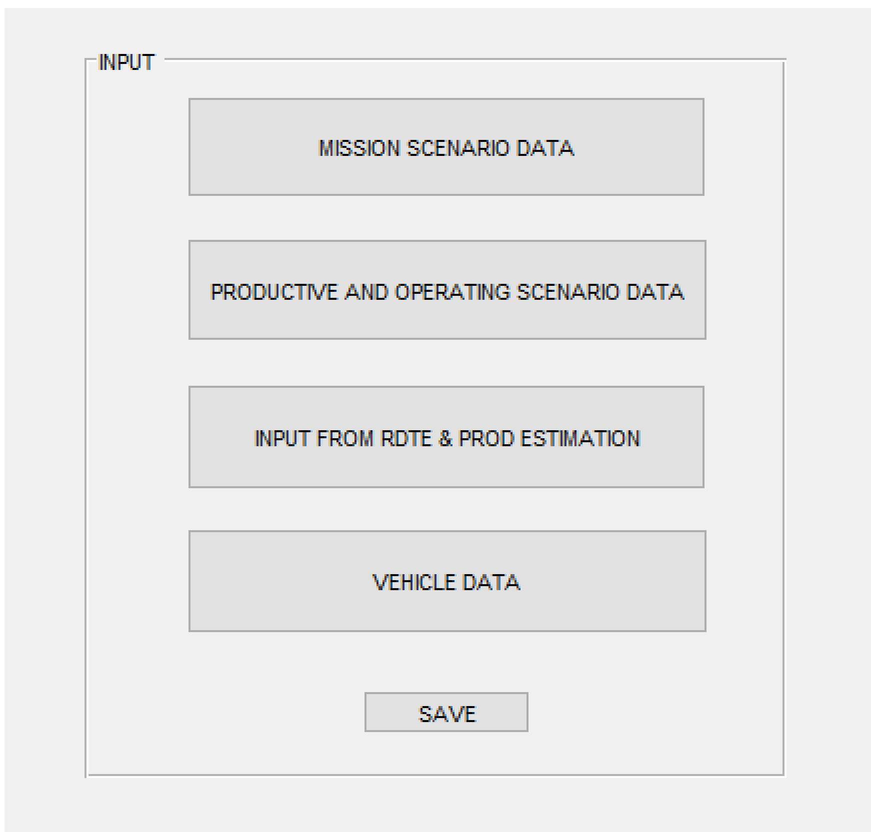


Figure 70: Screen of input of the MATLAB tool for the evaluation of costs of Cruise Air Vehicle.

In the input section, there are some pushbuttons linked to other GUIs where the user can enter the data for the estimation. The four input subsections have all the same structure. They have an area where are present some blank spaces that the user should fill with the data necessary for doing the cost evaluation. Near each field, it is present a static text that specifies the data that should be added and the unit of measurement required. In some case, button with a question mark is present close to the blank space. It is used to suggest information to the user for the data that are difficult to estimate or that are not so clear. The suggestions are taken from literature data or from the reference model, when thy can have general validity.

Outside that area, there are other four buttons:

- SAVE; it is used for saving the inputs. They will be saved into the Excel file called "DOC_CAV". If this file does not exist in the folder of program, it is created automatically by the tool when the SAVE button is pushed. If it is present, the data are saved in the proper sheet, overwriting what it is in the file.
- CANCEL; if it is pushed, the data present in the specific field of the program are deleted and substituted by zeros.
- RELOAD; it gives the possibility to fill the blank spaces with the data present in the "DOC_CAV" file, if it exists.
- INPUT; it is used to come back to the previous section of the input.

The excel file is created in the same folder where there is the program. Data is saved into different sheets called with the name of the relative screen to ease the data and file management.

In the input interface, the SAVE is also present the push button. It gives the possibility to save all the inputs inserted and to come back to the Home screen.

MISSION SCENARIO DATA opens the screen reported in *Figure 71*. In this section, the user should enter the input about the mission organization and features. The data of the following figure are the ones of the LAPCAT A2.

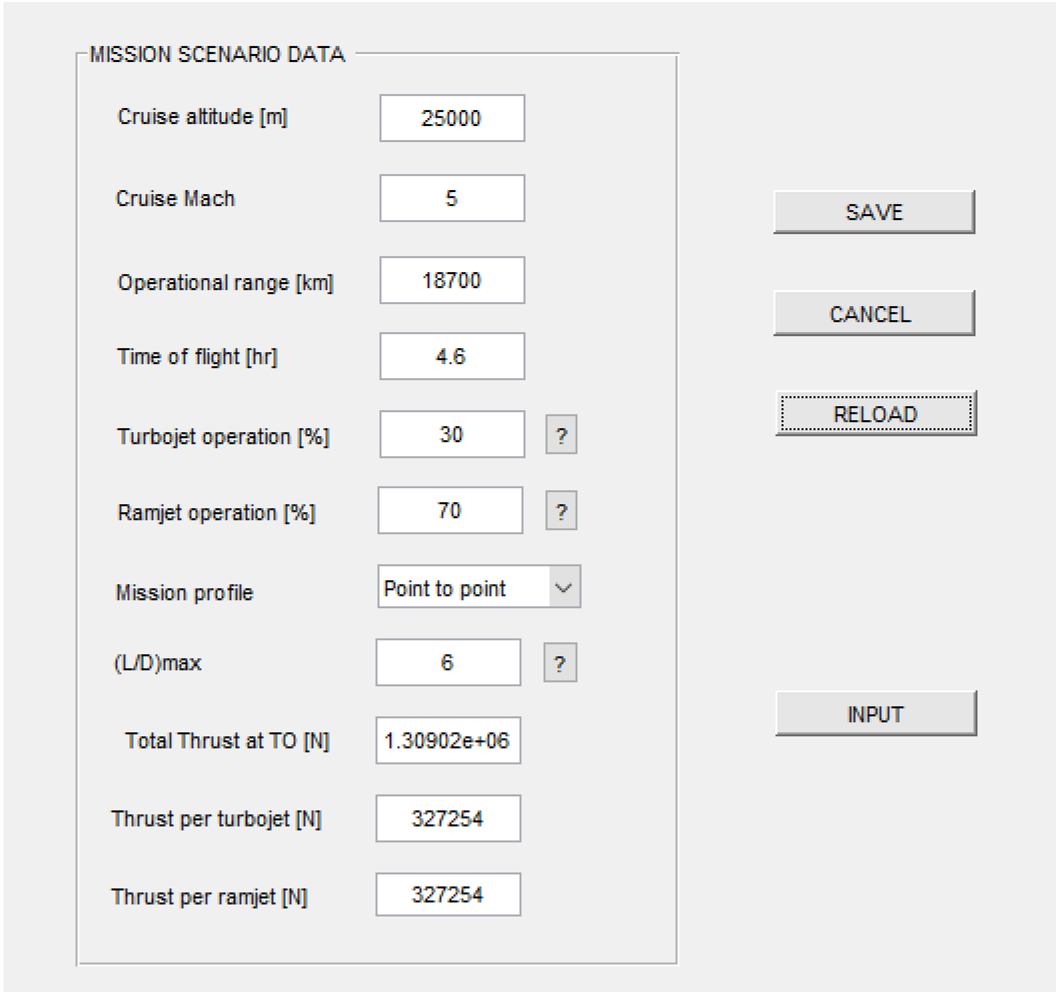


Figure 71: Mission scenario data screen of MATLAB tool for the evaluation of the cost of the Cruise Air Vehicle.

The first input required in the Mission Scenario Data is the cruise altitude, that must be in meters. After that, the cruise Mach is required. The cruise speed is evaluated thanks to this data. With the MATLAB function "Atmosisa.m", it is possible to evaluate the speed of sound at the cruise altitude, using International Standard Atmosphere model.

The next data is the operational range that must be in kilometer. After that, the user should enter the time of flight. For some cost evaluations, it is required the block time. It is the time between the wheels block are removed, before the initial movement for the taxi and the take-off, and they are replaced after the landing. It is difficult to evaluate this data but the ATA procedure [56] suggests increasing the time of flight of 0.25 hours, accounting for the preflight and post-flight phases. The block speed can be evaluated thanks to the operational range and the block time. It is lower than the cruise speed because the time considered is higher.

An interesting datum is period of time (expressed as percentage of the block time) in which turbojet and the ramjet engines are supposed to be used. These simple entries allow the tool to consider a multiplicity of propulsion system architectures, that can be modelled with a combination of an air-breathing and a ramjet engine. This input is used in particular in the equation for evaluating the maintenance of the engine. A typical value for a point to point mission profile can be 70% for the ramjets and 30% for the turbojets. Those data depend a lot from the type of mission, in particular from the mission profile, and from the engines configurations and their operating modes.

The next step is the mission profile definition. The hypersonic vehicle can reach the destination using different profiles. The most typical are the “point-to-point profile” or the “parabolic profile” that can be properly selected with a pop-up menu. The set of equations for LCC can be different according to the selected mission. In this work, only the equations for the point-to-point aircraft have been implemented.

Another input is the aerodynamic efficiency. As suggested in the info box, for a point-to-point vehicle the higher value of the lift-to-drag ratio should be used.

As far as thrust is concerned, maximum theoretical thrust available at the take-off for both air-breathing and ramjet engines shall be indicated.

The second screen of the inputs is about the productive and operating scenario. In this part, the data about the economic scenario of the vehicle are required. In this section, the major number of data is required. They are about the producive feature of the aircraft, as the number of units produced, and about the economic context, as some prductive features of the fuel.

In *Figure 72*, there is the interface of the productive and operating scenario data.

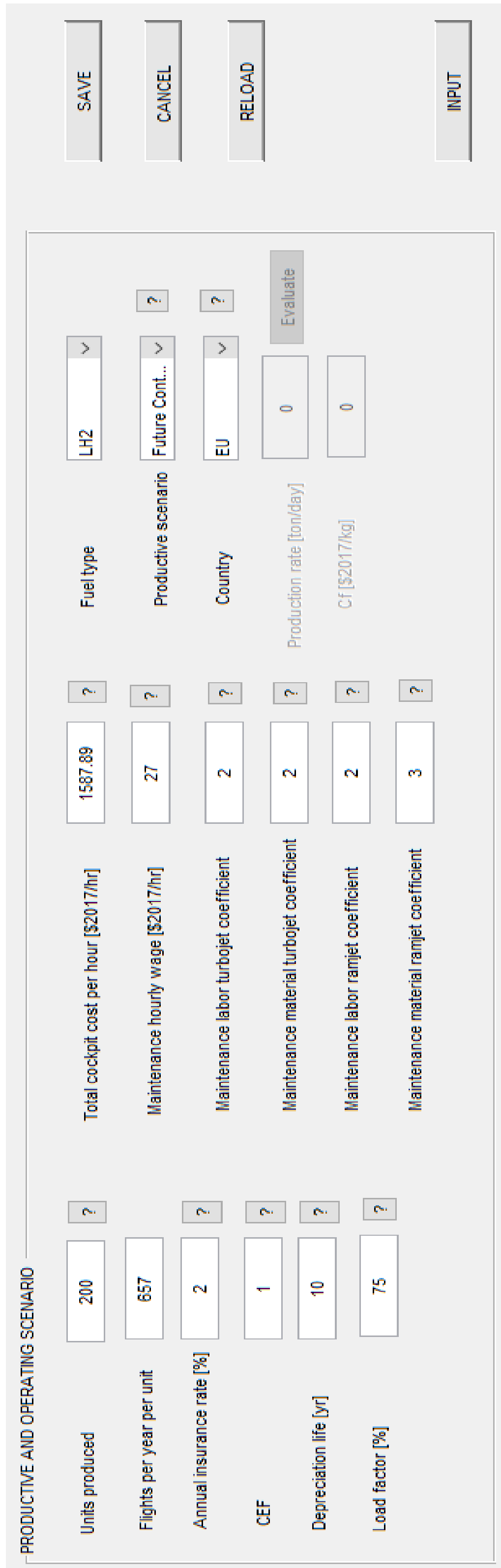


Figure 72: Productive and operating scenario data screen of MATLAB tool for the evaluation of the cost of the Cruise Air Vehicle

The first data required is the number of units produced. It is not directly linked with the evaluation of the direct operating costs, but it is necessary for the RDTE &Production costs evaluation. Increasing the number of the vehicle produced, the time of production of each element and its costs are reduced for the effect of the learning curve. The workers increase their expertise with the number of units built. This reduce the man-hours required for the construction and the costs associated. As a first estimation, the Break-Even Point (BEP) can be used. The Break-Even Point is the number of elements for which the total cost is the same of the total revenue. After reaching this value, all the costs are paid and there are only profits from the sales of the product.

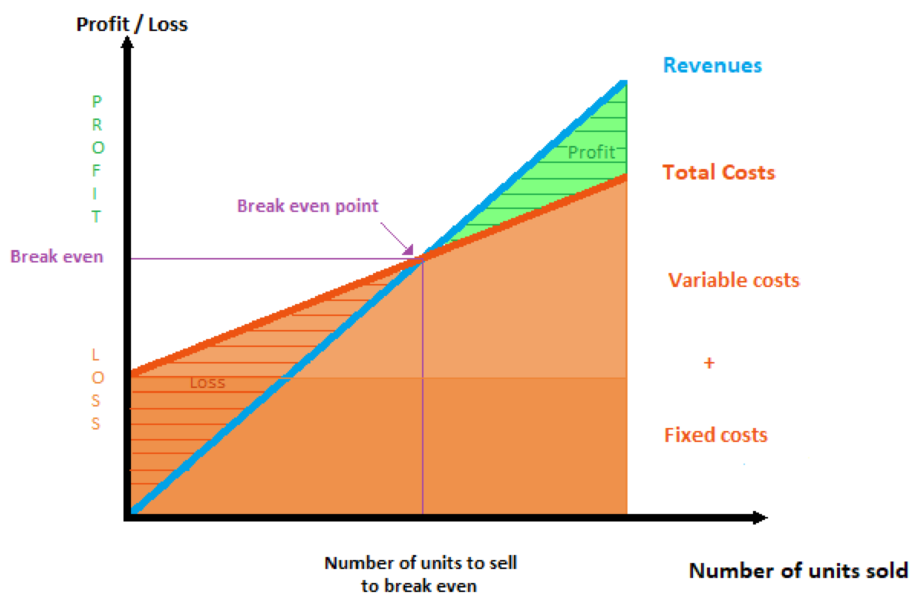


Figure 73: Break- even point.

The second data is the number of flights per unit of each year. It is used to evaluate the annual utilization of the aircraft. The utilization is obtained multiplying the number of flights per year for the block time. Its unit of measurement is the number of block hours per year.

The next value is the insurance rate. In the preliminary phases of design, it can be evaluated as a percentage of the initial acquisition cost. Usually for the first years, it about the 5% of the initial acquisition price. After four or five years, it becomes the 2% of the initial value [41]. The last value is suggested by the info box, if other information is not available.

The next data is the CEF, Cost Escalation Factor, a scaling factor allowing to update the CERs to the year for which the cost estimation will be done. Please, consider that the estimations inserted within the tool are actualized to the year 2017 and so the $CEF_{2017} = 1$. Values greater than one are referred for the futures years. Values lower than one is linked to the previous years. A simple way to estimate the CEF is considering the inflation rate:

$$inflation\,rate_{2017} : inflation\,rate_{req} = 1 : CEF \rightarrow CEF = \frac{inflation\,rate_{req}}{inflation\,rate_{2017}}$$

In *Figure 74*, there is the inflation rate for the United States of America from the 2010 to 2022. From the 2017, the data are only forecasts. It may not be true that for years after the 2017 the Cost Estimating Factor will greater than one, but it is possible to think that the inflation rate will gradually grow over the coming years. To a first approximation, it is correct to assume a greater value of the CEF for the futures years and a lower value for the previous years.

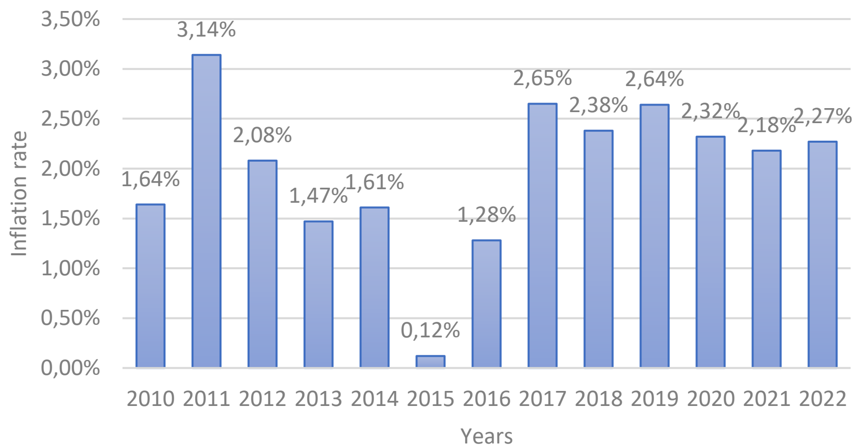


Figure 74: Inflation rate in the USA from 2010 to 2022 (data from [57]*).*

The next data, that should be entered, is the depreciation life. This value is difficult to estimate because it depends also on the airline company choices. This input is influenced by the type of technologies on-board. If they are mature and used in the civil aviation, the depreciation life is longer than they are new or closer to the space field. The value suggested is the same of the NASA method [41]. It is ten years. In reference [41], it is said that the depreciation period of civil aircraft is about fifteen years, but in the case of hypersonic aircraft it should be reduced to ten years.

The next input is the load factor. It is a ratio between the average value of payload present in the aircraft and the total value of payload that can be on board. It considers the fact of the airplane is not always full of payload. The value recommended is the 60%, as suggested in reference [41].

The hourly cost of cockpit is used for the evaluation of the direct operating cost of the crew. It includes the crew salary, the fringe benefits, training programs and travel expenses for the pilots [41]. It should be considered only the pilots and the co-pilots, because the costs of the flight attendants are indirect operating costs. It is possible to assume the presence of three members of the crew, because the range is quite long and the workload for the pilots is enough, even if the flight time is short. The value suggested is $1590 \frac{\$2017}{\mathrm{bhr}}$. This valued it is estimated thanks to equations in the Raymer [5] and it is confirmed by the data of Massachusetts Institute of Technology [39]. In the NASA report [41], it is suggested the value of $320\frac{\$1972}{\mathrm{bhr}}$. This value is obtained from an equation of the ATA, reference [56]:

$$cost\frac{\$1967}{bhr} = 0.05\frac{W_{GTO}}{1000} + K_C$$

Where:

- W_{GTO} is the gross take-off weight
- K_C is a constant: it is 118 for the turboprops, 155 for the turbojets and 200 for the hypersonic aircraft

No indications are present for the case of hypersonic. The value for the HST has been evaluated considering a turbojet aircraft with the same weight of the reference vehicle. That formula is increased applying a 6% annual growth for five years to obtain the value for the 1972. Further studies show that, for having the value for the hypersonic aircraft, the previous results should be increased by 33%. To use the same method to have the value of 2017 is not correct because the cost of cockpit per bock hour is too high. In fact, it is about $4600\frac{\$2017}{\mathrm{bhr}}$. Evaluating the inflation rate between the 1967 and the 1972, the value obtained for the NASA formula is about $1700\frac{\$2017}{\mathrm{bhr}}$, that is in line with the one obtained thanks to the relationships of the reference [5].

In reference [5], there are the following equations to evaluate the hourly cost of the cockpit:

$$Two - man\ crew\ cost = 74.5\left(V_C\frac{W_{GTO}}{10^5}\right)^{0.3} + 168.8$$

$$Three - man\ crew\ cost = 100\left(V_C\frac{W_{GTO}}{10^5}\right)^{0.3} + 237.2$$

Where:

W_{GTO} is the maximum take-off mass

V_c is the cruise speed.

These results are in the 2012 dollars and their value should be actualized using the factor 1.07 that is the ratio between the Consumer Price Index (CPI) of 2017 and the CPI of 2012 [58]. The values obtained are:

$$Two - man\ crew\ cost = 1171.91\frac{\$_{2017}}{bhr}$$

$$Three - man\ crew\ cost = 1587.89\frac{\$_{2017}}{bhr}$$

These values are confirmed by a research of the Massachusetts institute of Technology [59], that analyzed the total cockpit cost per block hour considering various types of aircraft. A three men crew cost for the 2016 is $1070\frac{\$2016}{\mathrm{bhr}}$. The cost of cockpit for a widebody aircraft is estimated in $1712\frac{\$2016}{\mathrm{bhr}}$. For a hypersonic aircraft it should be considered a three-man crew. The legislation [47] says that the presence of the third man is necessary for the long hauls routes to reduce the work of pilot and co-pilot. In the case of hypersonic vehicle, the flight time is short, but the duties for the crew are many and three men are necessary to do the best work as possible.

The maintenance hourly wage, also known as Labor rate on the NASA report [41], is the salary of the maintenance workers and it is necessary for the estimation of the maintenance cost. The value suggested is found in the MIT research [59]. The average annual wages and salaries of the in-house maintenance personnel for the 2016 is $76196\ \$_{2016}$. This value is the divided by the year's day and by 8, considering eight hours of work per day. The hourly wages obtained is about $27\,\frac{\$_{2017}}{hr}$.

The next four data are the maintenance coefficients of the engines. They are present in the NASA modified ATA CERs [41] to compare the maintenance of hypersonic aircraft with the one of the subsonic jet. They are necessary because the information about the maintenance activity is not easily available. In the case of hypersonic vehicle, there are not any data about maintenance because the projects of those aircraft are only in a design phase and the maintenance is not analyzed well. The values suggested for the maintenance coefficients of the engines come from the NASA report [41]. They consider the maintenance labor and the maintenance material of the turbojet and of the ramjet engines. They are: $K_{LTJ} = 2$ (maintenance labor of turbojet), $K_{MTJ} = 2$ (maintenance material of turbojet), $K_{LRJ} = 2$ (maintenance labor of ramjet) and $K_{MRJ} = 3$ (maintenance material of ramjet). They are derived from an analysis done by the reference [56] for the sonic aircraft and they are increased to obtain the value for hypersonic vehicles.

The last column of data of the interface about the operative scenario is linked to the definition of the fuel type and its productive scenario, for evaluating its cost. The hypersonic vehicle usually uses liquid hydrogen as fuel, because its chemical properties permits to the vehicle to reach its performances. This fuel is less used now and its cost is so high. This is due to also at the fact of the production rate, the quantity of fuel produced per day, is very low. Considering the fact of it will be one of the possible largest used fuel in the future, the production plants will become bigger than now and the production rate will growth. This will reduce the cost of the liquid hydrogen in the future operating scenarios. The cost evaluation of the fuel is based on a university research. The basic idea of the tool is not to oblige the user to insert the value of the fuel cost, but allowing to select the productive conditions and the programs will evaluate the cost per kilogram of LH2.

Some of the blank spaces and texts of the last column of the operative scenario data are grey, because they are deactivated. They will be activated once the previous fields are filled. This helps the user to enter the data in a correct way. The first step for the definition of the cost of fuel is to decide which fuel will be used. In fact, the NASA equation of the direct operating cost of the fuel does not depend on the type of the fuel but only on its cost. In the pop-up menu the user can click on LH2 or Other. If "Other" would be selected, the only part that will be activated the cost of fuel. He should enter the cost per kilogram of the fuel for the year 2017. The cost of liquid hydrogen depends on some factors as the productive scenario and as the country. The first one is linked to the production rate of the plants and to their technological level. The second one is mainly related to the cost of energy of the country. After clicking on LH2, the user should choose one of the five possible options for the operating scenario in the second pop-up menu. After that it should indicate the production country. In the third pop-up menu are present the United States of America and the European Union. After that, the user should click on evaluate to give to the program the possibility to estimate the cost of fuel. The text "Production rate" will be activated, if the user chooses "Other" in the operative scenario menu. In this case the user should enter the value of the production rate and the program will evaluate the cost of hydrogen for that production rate and for the country selected.

After filling all the blank spaces, the user pushes the button Save and he comes back to the Input screen.

The next screen of input is the one of the data about RDTE and production. The inputs are the production and the acquisition costs of the airframe and of the engines.

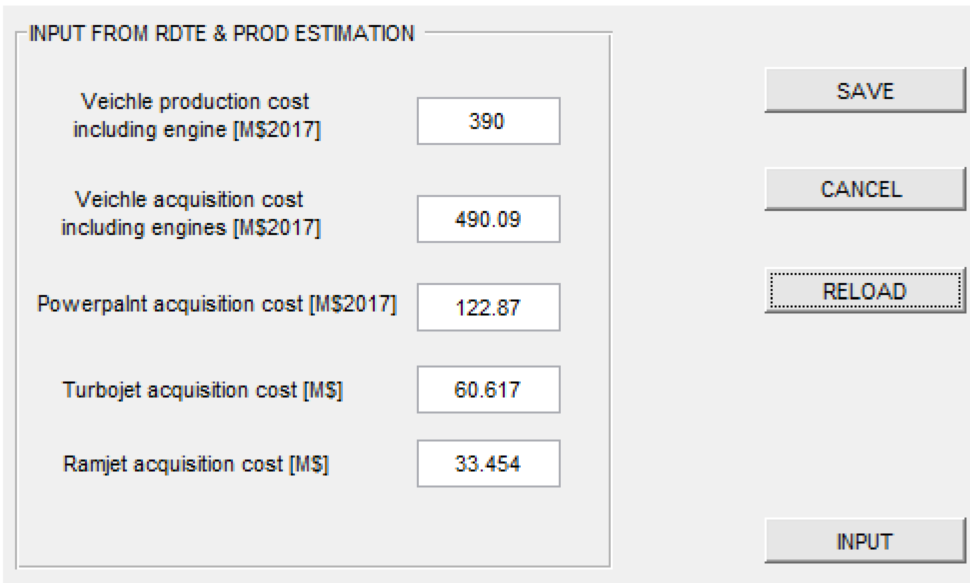


Figure 75: RDTE and production data screen of MATLAB tool for the evaluation of the cost of the Cruise Air Vehicle

In this screen the user should enter the data from the research, development and test and production phases of the projects. They are necessary for the evaluation of the insurance costs, depreciation costs and maintenance costs.

The first data required is the vehicle production cost including the engines. The second one is the vehicle acquisition costs, considering again the engines. The last three data are the powerplant acquisition costs, i.e. turbojet acquisition cost and ramjet acquisition costs. These values are not suggested, because it is supposed that the user knows the cost of the vehicle. If the user is not aware of these costs, some simple but less precise methods can be used. They are suggested by the reference [3] and [41]

When the tool will be completely developed, it will be possible to evaluate the cost of RDTE and production phases. In this case this input will be substitute by other set of data useful for that estimation.

Also in this case, the user can come back to the Home screen after filling all the data fields. It is also possible to reload the data present in the Excel file "DOC_CAV".

The last set of input require is the "Vehicle data". It is about the features of the vehicle, as its weights.

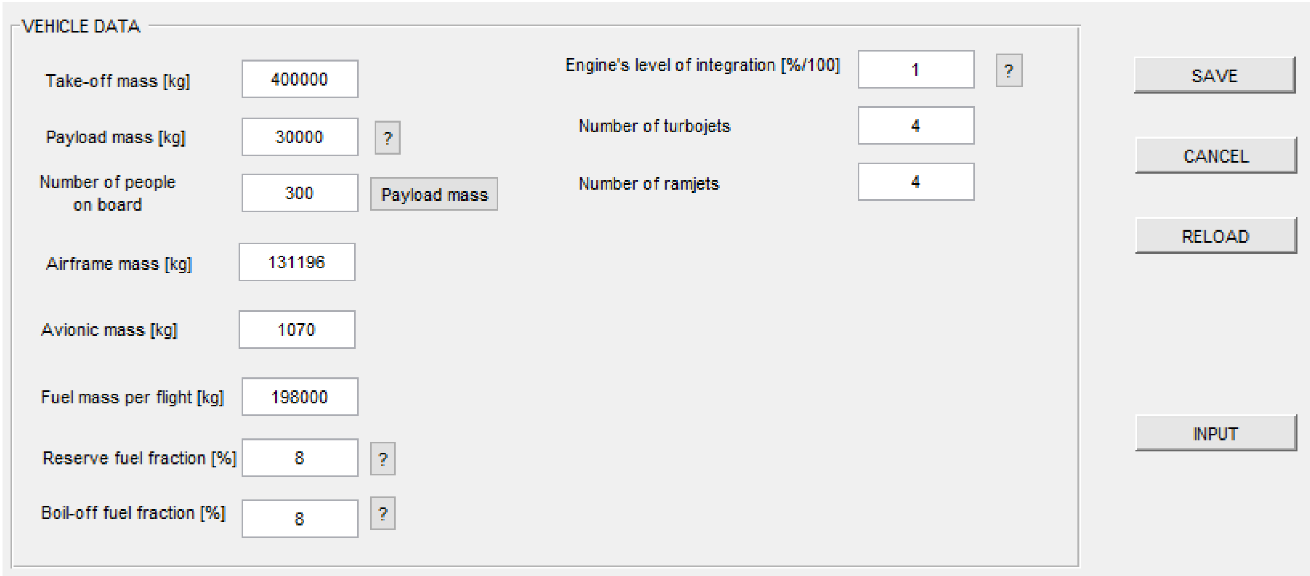


Figure 76: Vehicle data screen of MATLAB tool for the evaluation of the cost of the Cruise Air Vehicle

In this case, the data required are the physical features of the aircraft. In particular, all the masses should be entered, because the NASA equations have a strong dependency from the weights of the aircraft.

The first one required is the maximum take-off mass. After that, it should be entered the payload weight. If it is unknown, the info-box suggests filling the field of the number of passengers. This blank-space will be activated, once the user clicks on the button with the question mark. The user should push the button called "Payload mass" and the program will evaluate the payload mass and will fill the specific field. According to the legislation [60], it is considered a mass of 100 kg for each passenger. As it is possible to see in Table *17*, a mass of 80 kg is considered for each person on board, regardless of gender, and 20 kg for the baggage of each one.

Maximum seating capacity of aircraft (including crew)	Adult (Male) [kg]	Adult (Fem) [kg]	Infant [kg]	Child [kg]	Adolescent (Male) [kg]	Adolescent (Fem) [kg]
7 - 9	86	71	17	44	65	58
10 -14	86	70	16	43	64	58
15 -19	85	69	16	43	63	57
20 -39	84	69	16	42	63	57
40 -59	83	68	16	42	62	56
60 -79	82.5	67.3	16	41	61.4	55.4
80 -99	82.5	67.1	16	41	61.2	55.3
100 - 149	82	66.9	16	41	61.1	55.2
150 -299	81.8	66.7	16	41	60.9	55
300 - 499	81.4	66.3	16	41	60.6	54.8
500 -	81.2	66.1	16	41	60.5	54.7

Table 17: Suggested standard passenger weights [60].

The other masses required are the mass of avionics, airframe and mass of fuel for each flight. In the case of hypersonic aircraft, the fuel mass is about the half of the maximum take-off mass. The avionics mass is the lower value in the breakdown mass. The airframe weight considers the weight of all systems and of the structures.

Other two important data required are the reserve of fuel and the reserve for the boil-off of the fuel. Both are a percentage of the total fuel mass. The first one is mandatory for each aircraft and the legislation gives some guidelines for the evaluation of the mass of fuel that should added. Each airline company has an own policy to manage this aspect and each of them decides how much extra fuel is necessary, respecting the regulation [47]. In any cases, safety of the passengers should be guarantee and any mistake will be ratified by the authorities. The evaluation of the reserve of fuel depends on many factors, as the type of aircraft or the type of mission. It should give to the aircraft the possibility to reach an alternative airport, if the designated one is not available. It also should permit to the aircraft to flight an extra time safely. In the case of hypersonic aircraft, it is too soon to know this value precisely, because both the aircraft features and the mission characteristics (as the presence of alternative airports) are not well defined. As suggested in the NASA report [41], the reserve of fuel fraction is a percentage of total fuel mass. In particular, if the user does not know this data, it is recommended to use the 8%.

The boil-off fuel fraction is the percentage of extra fuel necessary to guarantee the quantity of vapor of liquid hydrogen required by the appropriate subsystems. One example of these systems is the TEMS, Thermal and Energy Management System, of the LAPCAT MR2. It uses the vapor of liquid hydrogen for cooling some parts of the structure as the cabin compartment. The LH2 is cryogenic. It will be useful to take advantages from this property. The value suggested is a percentage of the fuel mass. It is the 8%. This value is decided thanks to a preliminary university study about a vehicle with the same features of the LAPCAT MR2. One of the objective has been the sizing of the fuel tanks. In this case, the total extra fuel (considering the reserve fuel and the boil-off) was the 16% of the fuel mass. Considering that for the reserve fuel the value proposed is 8%, the reserve for the boil-off should be 8%.

The last part of the data is about the propulsive features. In particular, the user should enter the number of ramjets on of the turbojets on board the aircraft.

The engines' integration level is a very interesting data. It shows the level of integration between the ramjets of the turbojets. It is a value between zero and one. One means that there is complete integration between the turbojets and the ramjets, zero means that there is not integration. In the case of the LAPCAT A2, this value is one. It depends on the structure of the scimitar engine, where the ramjets and the turbojets are "present" in the same structure. In the case of the LAPCAT MR2, this data cannot be one. This vehicle uses evolution of turbojet and ramjet that share only the intakes. A plausible value could be 0.5. This factor is used for the allocation of the cost and for the maintenance analysis. In the NASA cost estimation relationships, it does not appear clearly. It is useful for the other cost evaluations.

Also in this case, after filling all the blank spaces, the user should push the buttons Save and Home to come back to the input screen. In the input interface, it should click on the "SAVE "button to go to the Home screen.

After that, the user should click on the button for obtaining the results. The only button activated is the DOC one in the part of baseline cost estimation. The program has now only the equations for the evaluation of the DOCs of the baseline. In the future developments, it will be a complete tool for evaluating the life cycle cost of the aircraft. Another important aspect is the evaluation of the impact of the technologies. Implementing a new set of relationships, it will be possible to evaluate how a change in the technologies on board can change the value of each voices of cost of an aircraft program.

In *Figure 77* it is possible to see the screen of the DOC estimation for the LAPACAT A2.

In the left side of the screen, the user can select the units of measurement to plot the results and then accessing to the right part of the estimations.

The DOCs are divided according to the reference [41]. For each cost item of Direct Operating Cost of maintenance there is an info-box that explains what it is. Because of NASA cost evaluation relationships [41] have been used and it has been decided to give to the user the possibility to see the cost of each item of the direct operating cost of maintenance. After those parts, there is the total of the maintenance costs.

The last field is the total direct operating costs of the aircraft.

At the right side, there is an area for a pie graphic that shows the percentage of each previous DOCs items. It will appear after the user pushes the DOC button.

As it is possible to see in *Figure 77*, at the right side of the graphic there is a legend that shows what is each slice. It is also present the percentage compared to the total DOCs. All the numbers are not so visible because the slices of the graphic are only a little part compared to the major cost item, that in this case is the fuel.

The maintenance cost is considered split in each of its component and this does not help to understand better the graphics.

It should be important to remember that the data evaluated are saved into the Excel file "DOC_CAV" where there are also the input data. They are saved in a dedicated sheet for helping the user to elaborate and to process them with other programs.

This MATLAB tool is used for the cost evaluation of the LAPCAT A2, that is presented in the next chapter of the thesis. In this case the for the post processing of the data, it is used Excel, because it is easier to export the data and the graphics in Word.

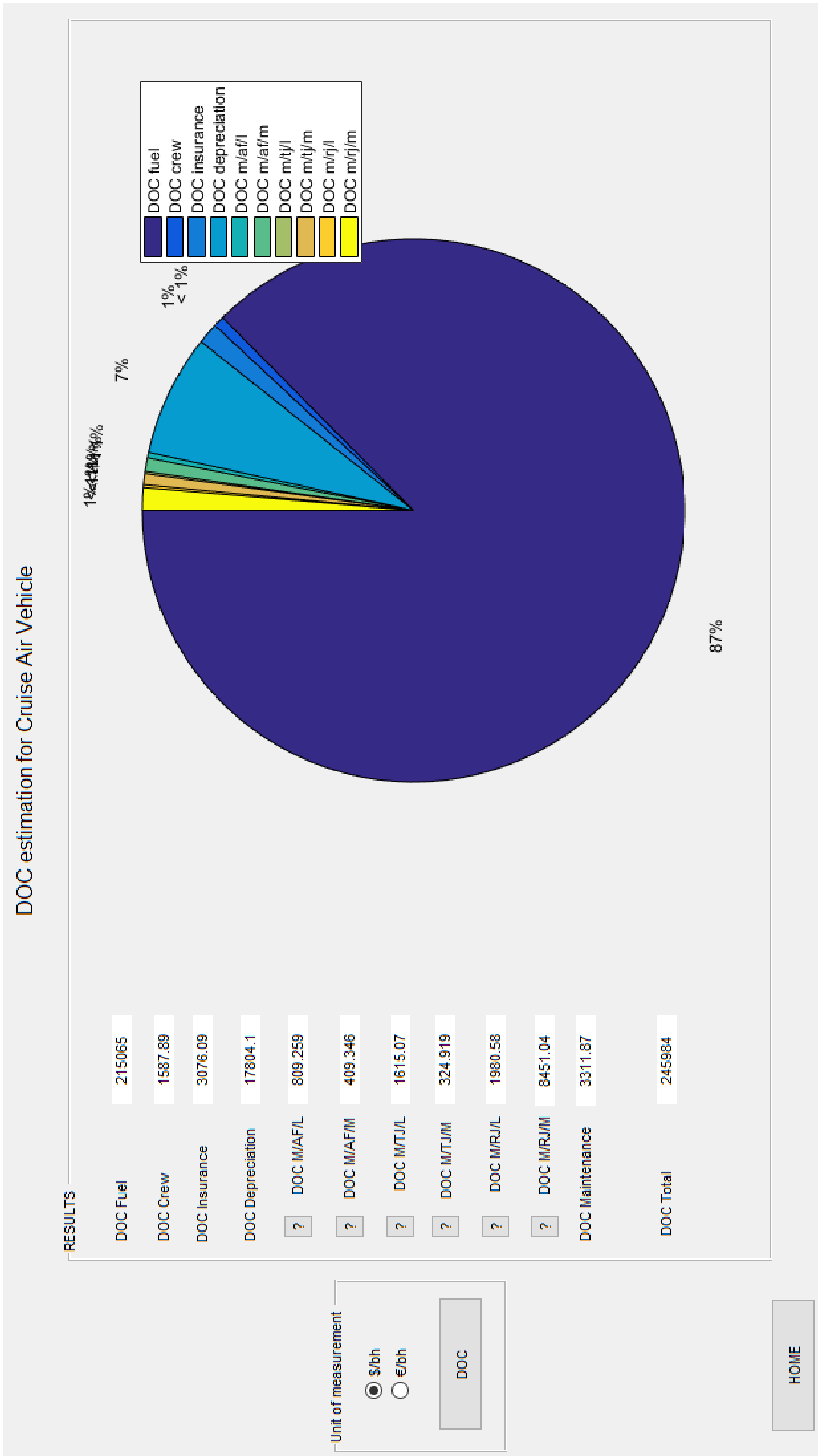


Figure 77:DOC evaluation screen of MATLAB tool for the evaluation of the cost of the Cruise Air Vehicle

7. LAPCAT A2 Direct Operating Costs Estimation

In this last chapter of the work, the direct operating costs estimation for the LAPCAT A2 are presented.

The first part summarizes all the inputs required by the MATLAB tool for the cost estimation.

Then, the results of the cost evaluation for the LAPCAT A2 are presented and commented. In addition, a comparison with DOCs of a subsonic aircraft is carried out.

The third part reports the evaluation of the direct operating costs considering the different productive scenarios of liquid hydrogen. The direct operating cost of fuel is the most important cost items and it is interesting to see how the cost changes with the price of fuel.

In the last section, there are the results obtained with the application of the equations modified with the introduction of the Breguet formula of the range. This formulation is interesting because it allows appreciating the effect of the specific fuel consumption and the aerodynamic efficiency on the DOC. Indeed, as previously discussed, they are two technological parameters measuring some technological improvements linked for example to the exploitation of a different propulsive system or a different aerothermodynamic configuration.

7.1 Input Data

The first step for the cost valuation is the definition of the data for the reference vehicle, the LAPCAT A2.

Figure 78: LAPCAT A2 [19].

The inputs required by the tool are not completely available in literature and some of them have been estimated.

In the following sections, there are the tables with the data required by the MATLAB program for the direct operating costs evaluation. They are subdivided following the same structure of the tool. In the third column of the table, there are the values of the LAPCAT A2. Some of them are present in literature. Others are estimated considering different references.

Mission Scenario data

The first set of input is about the Mission Scenario data. It is about the features of the mission, as the cruise altitude or the cruise speed (Table *18*).

Mission Scenario data			
Cruise altitude	z_cr	m	25000
Cruise Mach	M		5
Operational Range	R_T	km	18700
Time of flight	t_f	hr	4.6
Rate of use of turbojet	r_tj	%	30
Rate of use of ramjet	r_rj	%	70
Lift-to-drag ratio	L_D		6
Thrust at the take-off	T	N	1309016
Thrust of turbojet	T_tj	N	327254
Thrust of ramjet	T_rj	N	327254

Table 18: Mission scenario data for the LAPCAT A2.

The value for the cruise altitude and the cruise Mach are taken from the reference [22]. It is a study about hypersonic air vehicles and, in in the first part, there is the comparison between different hypersonic aircrafts that have been studied. In this reference, there is also information about the aerodynamic efficiency of the LAPCAT A2. The range and the information about the time of flight can be taken from [19]. In this report, there is the review of the LAPCAT project.

For the rate of use of turbojets and the ramjets, it is used what it is written in the NASA report [41]. The rate of use of turbojet is lower than the one of the ramjet because this engine is used only below Mach 3. This is a very short part of the time of flight.

For the data about the Scimitar engine, the reference [38] is used. This is a paper about the performance of the scimitar engine. The thrust of one engine at the take-off is about $327\ kN$. In the LAPCAT A2, there are four engines. This, the total thrust at the take-off is of about $1309016\ N$ (T_{TO})

The NASA equations require the thrust of both the ramjet and turbojet. In the Scimitar engine, they are completely integrated. In this case, it is difficult to estimate the thrust of kind of engine. It is assumed that the turbojet and the ramjet have the same thrust, that is the take-off thrust of the Scimitar engine:

$$T_{TJ} = T_{RJ} = 327254\ N$$

Productive and Operating Scenario data

The second set of inputs are mainly related to the Productive and Operating scenario. It is about some economic data that are useful for the estimation, as the fuel cost or the utilization of the aircraft (Table *19*).

Productive and Operating Scenario data			
Number of units produced	Unit_produced		200
Number of flights per year	LR		657
Annual insurance rate	IR	%	2
Consumer estimation factor	CEF		1
Depreciation life	L_d	yr	10
Load factor	LF	%	75
Hurly cost of cockpit	Cost_crew	$2017/hr	1587.89
Hourly wage of maintenance worker	Wage_maint	$2017/hr	27
Coefficient of turbojet labor	K_LTJ		2
Coefficient of turbojet material	K_MTJ		2
Coefficient of ramjet labor	K_LRJ		2
Coefficient of ramjet material	K_MRJ		3
Production rate of LH2	PR	ton/day	50
Productive scenario			Future Continuous
Production country			Europe
Cost of fuel	Cf	$2017/kg	4.83

Table 19: Productive and operating data scenario for the LAPCAT A2.

The first term is the number of units produced. In the reference [19], it is considered a number of 100 units. Further studies have underlined that the right number to have profits is 200 airplanes. Of course, considering the same timeframe means that the number of flight per year should be increase from 296 of the reference [19] to 657. In future, exploiting the results of a business case evaluation, additional considerations related to fleet management will be inserted.

The insurance rate can be assumed of about 2% [41]. The insurance rate gives the possibility to evaluate the direct operating cost of the insurance. At the beginning of the operating life, the insurance rate of an aircraft is expected to be greater than 2% but this value has been selected considering a scenario in which the aircraft has been in service since some years. Usually, when this datum is not available, the cost of insurance is evaluated as a percentage of the acquisition cost of the aircraft, because it is not possible to use other methods.

The Consumer Estimation Index, numerical value that gives the possibility to update the cost equations to the year of estimation. Considering that the reference year for the case study is 2017, the CEF value has been set to 1, because all the costs are in US Dollars of 2017.

The value of the depreciation life can be seen as the time when the aircraft loses its value. It depends on the airline policy and the technologies on board the aircraft. The typical value for a subsonic jet is about 15 to 20. For a hypersonic aircraft, it is suggested 10 years [41].

The load factor, i.e. the percentage of payload assumed to be present in each flight has been assumed equal to the 75% [19].

The hourly cost of cockpit has been estimated thanks to mathematical relationships present in the reference [5]. These equations depend on the maximum take-off weight and the cruise speed. For a hypersonic aircraft, it is assumed the presence of three crew members, considering the high duties of this type of flight. This valued is also confirmed by the reference [39], where are present the economic data of the major U.S. airline company. The equation of the reference [5] has been updated, because they are in $\frac{\$_{2012}}{hr}$. It is:

$$Three - man\ crew\ cost = att * 100\left(V_C \frac{W_{GTO}}{10^5}\right)^{0.3} + 237.2 = 1587.89 \frac{\$_{2017}}{\mathrm{bhr}}$$

$$att = \frac{CPI_{2017}}{CPI_{2012}} = \frac{245.120}{229.594} = 1.07$$

The values of the CPI_{2017} and CPI_{2012} are taken from the reference [51].

The wage of maintenance worker is evaluated thanks to the reference [39]. Taking into account the average annual wage and salaries of the maintenance employees and considering eight hours of work per day, the requested input has been estimated.

The coefficients describing peculiar aspects of maintenance of ramjet and turbojet have been estimated following indications reported in [41]. They are necessary to evaluate the cost of the maintenance of a hypersonic vehicle. Those coefficients allow to make a comparison of the maintenance of required from hypersonic engines with the one of large subsonic jet. They consider both the part of maintenance labor and the part of maintenance materials. In the reference [41], they are evaluated considering the data of the reference [1] that are about subsonic and sonic aircrafts. The NASA study has modified these data suggesting a feasible way for evaluating the maintenance of hypersonic aircrafts.

The other inputs of this section are linked with the cost of fuel. In the case of the LAPCAT A2, liquid hydrogen shall be considered, assuming Europe as production country and “Futures continuous” as production. According to the reference [48], this selection corresponds to a production rate of about 50 ton/day. The production rate is not only linked with the quantity of fuel produced by the plant but also to the technological level of the industry. With the previous data, a fuel price is $4.83 \frac{\$_{2017}}{\mathrm{kg}}$ is suggested by the tool.

RDTE and Production data

The next set of inputs comes from the RDTE and production costs estimation (Table *20*).

RDTE and Production Data			
Production cost of the aircraft	C_HST_prod	M$ 2017	390
Acquisition cost of the aircraft	C_HST	M$ 2017	490.09
Acquisition cost of turbojet	C_TJ	M$ 2017	60.62
Acquisition cost of ramjet	C_RJ	M$ 2017	33.45

Table 20: RDTE and productive data for the LAPCAT A2.

The reference [19] provides useful data. In particular, it informs that the engines development cost of the is about 8147 M€ in the 2006. The development cost of the aircraft is about 14500 M€ in the 2006. The total development cost is about 226000 M€ in the 2006. Assuming a total production of 100 vehicles and the 85% of the learning factor, the production cost of the first vehicle is 979 M€ in the 2006. The average vehicle sales price is about 639 M€ of the 2006, including full development and recovery.

These data could be a reference but cannot be used because it is assumed a number of 200 vehicles. Recent studies show that the production cost of the LAPCAT A2 is about 390 M€ in the 2017.

The first method used for estimating the acquisition cost of the vehicle comes from Roskam [3]. The acquisition cost depends on the cost of manufacturing and on the profit. A simple way to estimate the profit is to consider it as a percentage of the manufacturing cost. This is an approximated way to evaluate the profits, because they can change according to the market conditions. The profits are usually the 10% of the manufacturing costs. It has:

$$C_{acq} = C_{man} + C_{pro}$$

$$C_{pro} = F_{pro} * C_{man}$$

$$C_{acq} = 1.1 * C_{man} = 1.1 * 390 = 429\ M€$$

This value seems to be consistent with some researches, but it is too approximated.

In the reference [41], there is a method to evaluate the acquisition cost of the aircraft and of each component. It is based on the technical features of the aircraft and of each part. All the coefficients of the equations must be in the International System of units. Those formulas are developed for 1972. They must be actualized using the actualization factor, that can be evaluated as the ratio of consumer price index of the year of estimation and the CPI of 1972. The values for the CPIs come from the reference [51]. The coefficient for updating the cost expressions is:

$$att = \frac{CPI_{2017}}{CPI_{1972}} = \frac{245.120}{41.8} = 5.8641$$

The acquisition cost of the vehicle, normalized using the maximum take-off weight, is:

$$\frac{C_{HST}}{W_{GTO}} = \frac{C_{AF}}{W_{GTO}} + \frac{C_{TJ}}{W_{GTO}} + \frac{C_{RJ}}{W_{GTO}} + \frac{C_{AV}}{W_{GTO}}$$

It is composed by:

- Cost of the airframe

$$\frac{C_{AF}}{W_{GTO}} = att * \frac{855\ W_{AF}^{0.68}\ M^2}{W_{GTO}}$$

Where

W_{AF} is the weight of the airframe

M is the cruise Mach number

The airframe cost for the LAPCAT A2 is:

$$C_{AF} = att * 855\ W_{AF}^{0.68}\ M^2 = 378.70\ M\$_{2017}$$

- Cost of turbojet

$$\frac{C_{TJ}}{W_{GTO}} = att * 6300\ N_{TJ}^{-0.15}\ T_{TJ}^{-0.33}\ \left(\frac{T}{W}\right)_{GTO}$$

Where

N_{TJ} is the number of turbojets

T_{TJ} is he thrust of the turbojet

$\left(\frac{T}{W}\right)_{GTO}$ is the thrust to weight ratio at the take-off

The turbojet cost for the LAPCAT A2 is:

$$C_{TJ} = att * 6300\ N_{TJ}^{-0.15}\ T_{TJ}^{-0.33}\ \left(\frac{T}{W}\right)_{GTO} W_{GTO} = 60.62\ M\$_{2017}$$

- Cost of ramjet

$$\frac{C_{RJ}}{W_{GTO}} = att * \frac{33900\ A_{C_{tot}}^{0.9}\ M^2}{W_{GTO}}$$

Where

A_C is the total ramjet cowl area

The ramjet cost for the LAPCAT A2 is:

$$C_{RJ} = 33900\ A_{C_{tot}}^{0.9}\ M^2 = 33.45\ M\$_{2017}$$

- Cost of avionic

$$\frac{C_{AV}}{W_{GTO}} = att * \frac{2760\ W_{AV}}{W_{GTO}}$$

Where

W_{AV} is the weight of avionics

The cos of avionic of the LAPCAT A2 is:

$$C_{AV} = 2760\ W_{AV} = 17.32\ M\$_{2017}$$

The total acquisition cost for the LAPCAT A2 is:

$$C_{HST} = C_{AF} + C_{TJ} + C_{RJ} + C_{AV} = 490.09\ M\$_{2017}$$

Evaluation of the Ramjet cost

These costs are used as fundamental input for the direct operating cost estimation. It should be noticed that for LAPCAT A2, the Scimitar engines are not the physical union of a ramjet and a turbojet machine. Despite of that their way of working can be represented by two main operating conditions, a ramjet-like and a turbojet-like operating mode, for the cost estimation it is necessary to know the acquisition cost of the turbojet and of the ramjets. It has been decided to use the previous equations of the acquisition cost of engines with the data of the Scimitar engine. The only data that is not present is the total cow area of the ramjet A_C and it should be estimated. There is not many information, in literature, about the cowl area of the Scimitar engine, because this is a very innovative propulsive strategy.

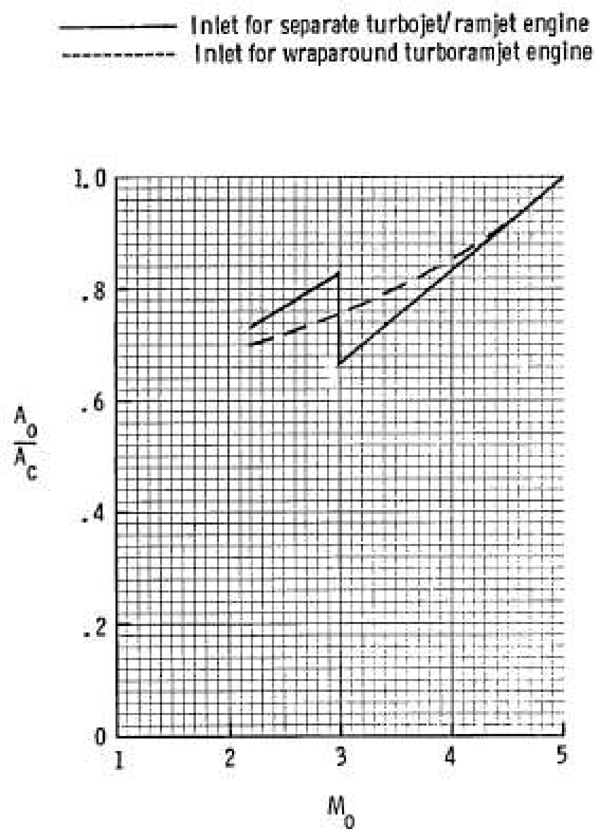


Figure 79: Inlet flow mass flow ratio for Mach between 2and 5 [61].

To evaluate the cowl area of the Scimitar engine A_C, it is used the *Figure 79* and the equation for estimating the air flow inside the inlet:

$$\dot{m} = \rho * A_0 * V$$

Where:

- $\dot{m}$ is the air flow rate in the intake; it is in $\frac{kg}{s}$
- ρ is the density of the air; it is in $\frac{kg}{m^3}$

- A_0 is the area before the intake; it is in m^2
- V is the speed of the air; it is in $\frac{m}{s}$

From that equation it is possible to obtain A_0:

$$A_0 = \frac{\dot{m}}{\rho V}$$

Thanks to *Figure 79*, it is possible to obtain the cowl area of the Scimitar engine.

In the reference [38], there are the performances of the Scimitar engine. They are shown in the Table *21*. They are used for the evaluation of the cowl area of the ramjet.

Altitude m	**Mach**	**Equiv. Ratio**	**Thrust N**	**Airflow kg/S**	**Air-fuel ratio**	**Flight Phase**
5.3	0.329	0.8	372254	519.9	42.87	Runway acceleration with reheat
1230	0.408	0.407	248134	477	84.28	Subsonic acceleration with reheat
16577	2.5	0.7	272771	284.2 (intake spilling)	48.98	Engine mode change subsonic phase
16577	2.5 (B-mode)	0.7	313105	349.5 (full capture)	48.98	Engine mode changes hypersonic phase
5900	0.9 (P-mode)	0.0749	81873	390.4	458	Subsonic cruise
25400	5	0.8	168348	173.6	42.87	Hypersonic cruise

Table 21: SCIMITAR engine performances [4]

To evaluate the cowl area, it is analyzed both the condition of subsonic cruise and of hypersonic cruise of the Table *21*.

The first step is to evaluate the density of air and speed for the condition of subsonic cruise. Thanks to the relationships of the International Standard Atmosphere, it has:

- z=6000m
- $\rho = 0.659\ kg/m^3$
- $c = 316.43\frac{m}{s} \rightarrow V = c * M = 284.787\frac{m}{s}$ (where c is the speed of sound)

The area of the ramjet is:

$$A_0 = A_C = \frac{\dot{m}}{\rho V} = \frac{390.4}{0.659 * 284.787} = 2.08\ m^2$$

It is decided to not consider the relationship of the *Figure 79*, because there is not data about the subsonic conditions. There are four engines in the LAPCAT A2, so the total cowl area is:

$$A_{tot} = 2.078 * 4 = 8.32m^2$$

After that it is considered the condition of hypersonic cruise. For evaluating the density of the air at the cruise altitude, it is used again the data of ISA. It has:

- z=25000m
- $\rho = 0.088\ kg/m^3$ (da verificare)
- $c = 295.07 \frac{m}{s} \rightarrow V = c * M = 1475.35 \frac{m}{s}$

It is now possible to evaluate the inlet capture area A_0 of the ramjet. It is:

$$A_0 = \frac{\dot{m}}{\rho V} = \frac{173.6}{0.088 * 1475.35} = 1.3371\ m^2$$

From the *Figure 79*, it is possible to see that the ratio between A_0 and A_C is one for Mach 5 the cowl area of a ramjet with the same features of the Scimitar engine is:

$$A_C = A_0 = 1.3371\ m^2$$

In the LAPCAT A2 there are four Scimitar engines. The total cowl area of the ramjets is:

$$A_{C_{tot}} = 1.3371\ * 4 = 5.3484 m^2$$

As said before, there are not data available about the structure of the Scimitar engine. It has been decided to evaluate the cost of the ramjet using the worst condition, i.e. the one that gives the higher acquisition cost. It is the case of subsonic cruise. In this situation, it has:

$$C_{RJ} = 33.454\ M\$_{2017}$$

For the hypersonic cruise, the acquisition cost of the ramjets is:

$$C_{RJ} = 22.44 M\$_{2017}$$

The total acquisition cost for the four engines is:

$$C_{eng_{TOT}} = C_{RJ} + C_{TJ} = 94.07\ M\$_{2017}$$

The total cost has been evaluated considering the cost of the turbojet component and of the ramjet component. According to this evaluation, the cost for the single Scimitar engine is:

$$C_{Scimitar} = \frac{C_{eng_{TOT}}}{4} = 23.52\ M\$_{2017}$$

Considerations on acquisition costs

To verify that they could be realistic values, it is updated the acquisition costs of the baseline of the NASA report [41] to the 2017. They are evaluated using the Same relationships applicate for the LAPCAT A2. They are:

	Baseline NASA [41]	**LAPCAT A2**
C_{AF}	446.04 M$2017	378.70 M$2017
C_{TJ}	51.73 M$2017	60.62 M$2017
C_{RJ}	45.09 M$2017	33.45 M$2017
C_{AV}	2.29 M$2017	17.32 M$2017
C_{HST}	565.83 M$2017	490.09 M$2017

Table 22: Acquisition cost for the Baseline of the reference [3]

It is possible to see how the cost of the two vehicles are not the same. This is due to the different structural features and performances. A comparison between the characteristics of the two aircraft is in Table *23*. The acquisition costs for the baseline of the NASA is higher than the one of the LAPCAT A2. The costs have the same order of magnitude and the same trends. Indeed, the cost of the turbojet is bigger than the one of ramjet. The main differences between the two groups is the cost of avionics, that is grater in the case of LAPCAT A2. The NASA baseline reported in [41] was designed in the 1972, when the avionics was not yet so present in the aircraft. The avionics is now fundamental in each aircraft, because it is not possible to control the vehicle without.

Thanks to the comparison with the acquisition cost of baseline, it is possible to use the evaluated acquisition costs for the LAPCAT A2 cost estimation.

Table *23* shows the features useful for the evaluation of the acquisition cost of the LAPCAT A2 and of the baseline. The characteristics of the two vehicles are completely different under many points of view. Indeed, even if the Mach number is quite similar, the operational range and the time of flight are different. Interesting is the thrust to weight ratio, because the two values are comparable. The one of the NASA baseline is higher than the one of the LAPCAT A2. Evaluating the weight and the maximum thrust at the take-off of the NASA reference it is possible to see how smaller they are compared to the ESA vehicle. The difference between the thrust at the take-off between the two vehicles is due to the fact that all the thrust of the Scimitar (and not only the contribution of the turbojet) is considered in the case of LAPCAT A2.

		NASA Baseline [41]	LAPCAT A2
Cruise Mach		6	5
Operational range	km	7400	18700
Time of flight	hr	2	4.6
sfc	kg/(N*hr)	0.113	0.088
L/D		4.6	6
Thrust to weight ratio at TO		0.482	0.334
Turbojet thrust	N	25800	327254
Number of turbojet engines		4	4
Total ramjet cowl area	m^2	7.73	8.32
Number of ramjet engines		9	4
Gross take-off weight	kg	218400	400000
Airframe weight	kg	98000	131196
Avionics weight	kg	1500	1070
Payload weight	kg	22700	30000
Load Factor	%	60	75
Fuel weight	kg	79000	198000
Fuel Reserve	%	8	8

Table 23: Comparison of features of the Baseline NASA and LAPCAT A2

The two aircrafts are designed in different years and with different project ideas. The NASA baseline is developed considering the production of one vehicle only. In the case of the LAPCAT A2, the estimation supposes a serial production.

The Scimitar engine (main features)

The costs, obtained thanks to the formula for the acquisition cost of reference [41], are used for the evaluation of the DOCs of the LAPCAT A2. The acquisition price of the propulsive system is a value that cannot be completely accepted, because the Scimitar engine is a “hybrid” between the ramjet and the turbojet. It is a great simplification to consider that the ramjets and the turbojets have the same features of the Scimitar. According to reference [38], the Scimitar is an air-breathing engine for the hypersonic flight that uses liquid hydrogen both as fuel and to precool the inlet. The air of the inlet is decelerated and refrigerated. It can be compressed and managed with a combustion system similar to the subsonic turbo-machinery. The Scimitar is derived from the Reaction Engine SABRE, designed for propelling the spaceplane SKYLON. The great advantage of the Scimitar is the possibility to fly effectively in subsonic, sonic and hypersonic flight with a single power plant. This aspect should be considered even in the case of failures. In fact, if the hypersonic flight is not possible, the vehicle can continue at subsonic speed. Furthermore, the sonic boom over populated areas will not be a problem. The Scimitar technology is based on the union of well-developed gas turbines practice and new leading-edge exchange technology. The Scimitar configuration is quite complex, because it should meet the requirements of a subsonic and hypersonic flight. It uses a three-shock intake for reaching the right value of the efficiency. The pre-cooler should limit the compressor inlet temperature. It consists of six segments. The compressor is a counter rotating two spools machine. It is driven by a stator-less counter rotating helium turbine. Some regenerator heat exchangers and circulators are positioned around the compressor. The Scimitar has two functioning-modes:

- P mode or hypersonic mode: when the exhaust from helium is directed to the core combustion chamber and nozzle;
- B mode or subsonic mode: when the exhaust helium is directed through the hub turbine of the fan to the bypass burner.

The Scimitar has two nozzles, one for the core engine and one for the bypass. The deviation of the helium happens using a diverter valve. The Scimitar has a bypass nozzle with a petal arrangement enabling its area to be modified with a wide range of opening depending on the flight conditions.

The structure and the performances of the Scimitar engine are unconventional. The acquisition costs evaluated before with the formulation of reference [41] cannot be correct. On the other hand, they are similar to the costs of the NASA baseline actualized at 2017. For this reason, it is decided to us them for the evaluation of the direct operating costs of the LAPCAT A2.

The Roskam method for evaluating the acquisition cost of the engine

In Roskam [3], there is a figure similar to the Figure 80. It gives the possibility to evaluate the cost of an engine, if its thrust at the take-off are known.

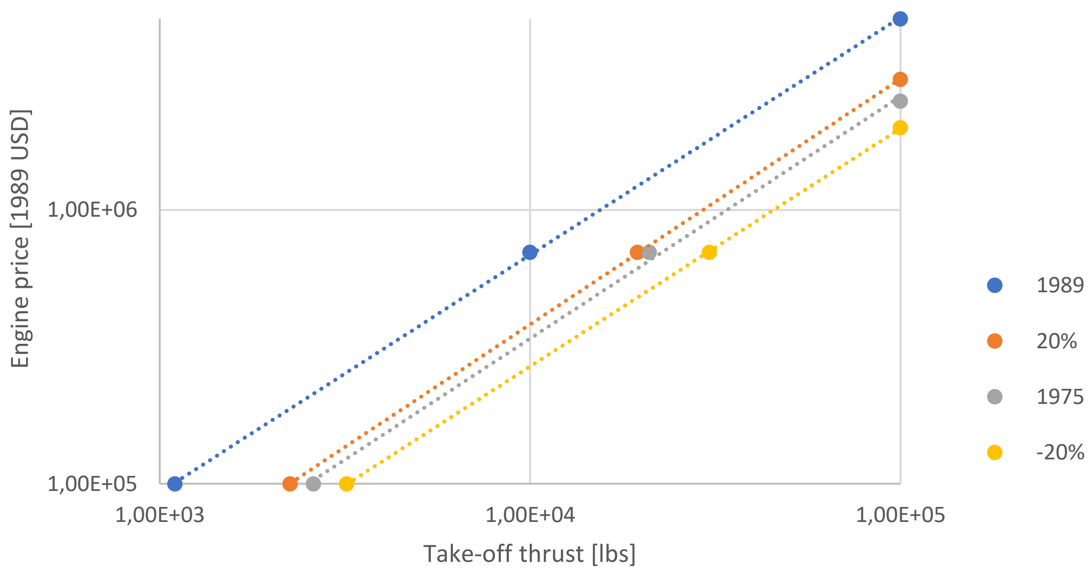


Figure 80: Relationship between engine price and the thrust at the take-off [3].

In the case of Scimitar, the thrust at the take-off is:

$$T_{TO} = 327254\ N = 73544.50\ lbs = 73.544 * 10^3 lb$$

Using this value in *Figure 80*, it has an acquisition price for the engine of:

$$C_{eng} = 4 * 10^6 \$_{1989}$$

This value must be update to the 2017, using the CPI [51]. The actualization coefficient is:

$$att = \frac{CPI_{2017}}{CPI_{1989}} = \frac{245.120}{124.0} = 1.98$$

The engine price actualized is:

$$C_{eng} = 7.90 * 10^6 \$_{2017}$$

This value is completely wrong. It has been predictable, because reference [3] analyzes only the case of the subsonic aircraft. The LAPCAT A2 is a hypersonic aircraft with a peculiar engine strategy. The relationship of reference [3] is not applicable.

Vehicle Data

The last set of input for the MATLAB tool is about the vehicle data Table *24*, where there are the features of the vehicle.

Vehicle Data			
Maximum take-off mass	W_GTO	kg	400000
Payload mass	W_pl	kg	30000
Number of passengers	N_pas		300
Airframe mass	W_AF	kg	131196
Avionics mass	W_AV	kg	1070
Fuel mass	W_fT	kg	198000
Reserve of fuel	K_R	%	8
Reserve of fuel for boil-off	K_boff	%	8
Integration level of the engines	I_eng	%/100	1
Number of turbojet	N_TJ		4
Number of ramjet	N_RJ		4

Table 24: Vehicle data for the LAPCAT A2

From reference [19], it is possible to know the maximum take-off mass of the aircraft and the numbers of passenger on board. The payload mass is evaluated considering that each person has a mass of 100 kg, in including luggage, suits and small emergency devices. In the same reference, there is also the load factor value. It is the 75% of the total payload mass.

The weight of the airframe comes from reference [62].

The weight of the avionics is evaluated thanks to a university research. It is possible to see how this weight is smaller than the other masses. The value of the fuel weight comes from the reference [63].

According to the reference [41], the reserve of fuel is the 8% of the total fuel mass. It is assumed another 8% for the boil-off.

The integration level of the engine is a factor that describes the integration between the turbojet and the ramjet. In the case of Scimitar engine, it is 1 because the ramjets and the turbojets are completely integrated in the same structure.

The number of Scimitar engines for the LAPCAT A2 is 4. So, the same is the number of ramjets and turbojets.

7.2 Cost estimation for the LAPCAT A2

With the previous sets of inputs, it is possible to evaluate the direct operating costs of the LAPCAT A2.

The cost estimation relationships come from the NASA report [41]. The results of NASA equations are in $\frac{cent}{ton*mile}$. For the cost estimation of the LAPCAT A2, the results should be in $\frac{\$}{block\ hour}$ or $\frac{€}{block\ hour}$. In reference [41], there are two coefficients for the conversion of the units of measurement. One gives the possibility to have the results in cost per flight. The second one gives the chance to have the cost per block hour. The coefficients are:

$$conv_1 = LF\left(\frac{W_{PL}}{2000}\right)R_T \rightarrow \frac{\$}{flight}$$

$$conv_2 = LF\left(\frac{W_{PL}}{2000}\right)680M\frac{V_B}{V_{CR}} \rightarrow \frac{\$}{bhr}$$

$conv_1$ should be divided by the block time t_B for having the cost per block hour. The block time is evaluated from the time of flight adding 0.25 hour as it is suggested by reference [41]. For the LAPCAT A2, it is:

$$t_B = 4.85\ hr$$

The previous coefficients for the LAPCAT A2 are:

$\frac{conv_1}{t_B} \rightarrow \ \$/bhr$	$5.1636 * 10^4$
$conv_2 \rightarrow \ \$/bhr$	$6.1216 * 10^4$

Table 25:Coefficients for the LAPCAT A2

For the cost estimation, it is decided to use the coefficient $conv_2$. The two coefficients have the same order of magnitude, but the second one is suggested by the reference [41].

For passing from Dollar to Euro, it is used the conversion factor of the 2017 (the same year of the costs in the relationships): $1\ €_{2017} = 1.051978\ \$_{2017}$.

The cost estimation for the LAPCAT A2 is:

	$\$_{2017}$/bhr	€$_{2017}$/bhr
DOC_Fuel	215065.20	226243.85
DOC_Crew	1587.89	1670.43
DOC_Insurance	3076.09	3235.98
DOC_Depreciation	17804.15	18729.57
M/AF/L	809.26	851.32
M/AF/M	1980.58	2083.52
M/TJ/L	324.92	341.81
M/TJ/M	1615.07	1699.02
M/RJ/L	409.35	430.62
M/RJ/M	3311.87	3484.01
DOC_Maintenance	8451.04	8890.31
DOC_tot	245984.36	258770.14

Table 26: Cost estimation for the LAPCAT A2.

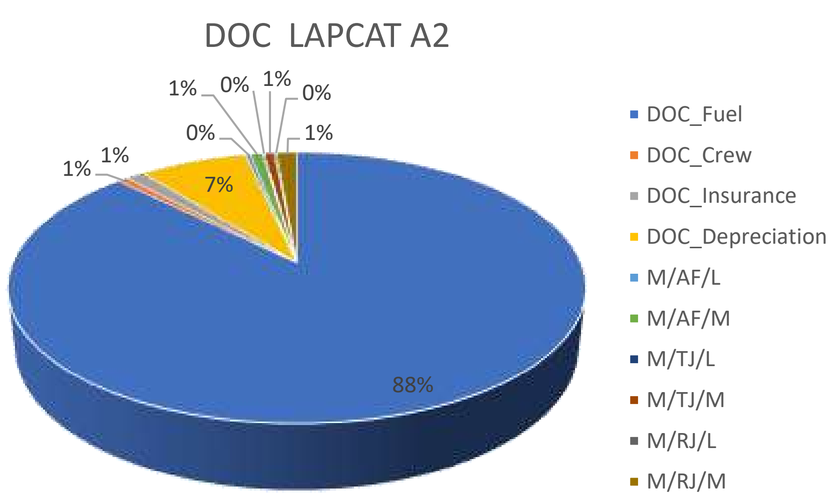


Figure 81: Direct Operating Cost for the LAPCAT A2

The *Figure 81* shows how the most important cost item is the direct operating cost of the fuel. The second item is the direct operating cost of depreciation. In *Figure 81*, there are all the parts of the direct operating cost of the maintenance. It is interesting to see that the costs of materials are greater than the labor costs.

In the reference [19], it is estimated that the annual operating cost for the LAPCAT A2 is about $553.8\ M€_{2006}$. If the liquid hydrogen is produced by electrolysis and liquefaction, DOC of fuel is the 83% of the operating cost. This value can be compared with estimation done using the NASA modified ATA CERs [41].

Reference [14] reports variable and fixed operating cost per block hour for Part 121 passenger air carriers. The operating costs are about for all type of aircraft are $ 4289 per block hours. The estimation was done in the 2013. The direct operating costs per block hour for a wide body airplane with more than 300 sets are shown in *Table 27*.

	COST PER BLOCK HOUR
	Wide body more than 300 seats
Fuel and oil	$ 10275
Maintenance	$ 1687
Crew	$ 1538
Tot Variable	$ 13500
Depreciation	$ 761
Rentals	$ 318
Insurance	$ 9
Other	$ 5
Tot fixed	$ 1093
Total	$ 14592
Block hours	191834 bhr

Table 27: The direct operating costs per block hour for a wide body airplane with more than 300 sets [64].

In this case, the variable costs are the cost of fuel, the cost of crew and the cost of maintenance. The fixed costs are the depreciation cost, insurance costs and rental cost (that is not considered in reference [41]).

For a subsonic aircraft, the operating costs per block hours are less than a hypersonic aircraft. It is interesting to see that in both cases, the most important cost item is the cost of fuel. In *Figure 82*, it is shown the DOC evaluation for a wide-body aircraft, with more than 300 seats. In this cost estimation, there are some items that are not present in the one of hypersonic aircraft. It is interesting to see the importance of the cost of crew, that in the case of hypersonic vehicle is not so relevant. In the subsonic case, the fuel cost is the 70% of the total direct operating costs. In the both cases, the depreciation cost has a comparable value.

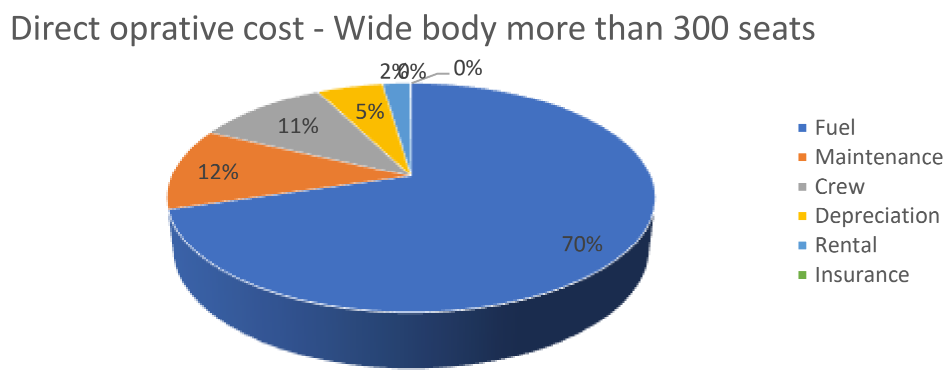


Figure 82: Direct operating cost - Wide body more than 300 seats – data from reference [64].

7.3 Comparison of the DOCs for different productive scenario of liquid hydrogen.

The Direct Operating Cost estimation shows how the fuel cost is the most relevant cost item.

It is interesting to analyze how the direct operating costs change with the variation of the fuel price, and in particular, the way in which assumption related to the envisaged operating scenario as well as the technology used to produce and manage liquid hydrogen. The cost of liquid hydrogen depends on many factors, as the production country or the production rate. The MATLAB tool gives the possibility to the users to choose the productive scenario of LH2 production, that are directly linked to the production rate and to technological level of the productive plants.

In the following tables, there are the cost estimations for different productive scenarios of LH2. There is also the comparison between two different production countries: the United States and Europe.

Because of the only direct operating cost that change is the cost of fuel, in the following tables, it is shown only this cost item and the total DOCs.

The first productive scenario is called "Today small-plant". The production rate is of 2.29 ton per day. The cost of fuel for the Europe is 13.21 S_{2017}/kg (12.58 S_{2013}/kg). For the USA, it is 6.91 S_{2017}/kg (6.58 €$_{2013}$/kg). This difference is due to the different cost of the energy. In the United States, it is the half than the Europe [18].

	EU		**USA**	
	$$_{2017}$/bhr	**€$_{2017}$/bhr**	**$$_{2017}$/bhr**	**€$_{2017}$/bhr**
DOC_Fuel	560149.10	589264.53	292987.37	308216.27
DOC_tot	591068.27	621790.81	323906.53	340742.55

Table 28: DOC for the LAPCAT A2 – today small-plant scenario.

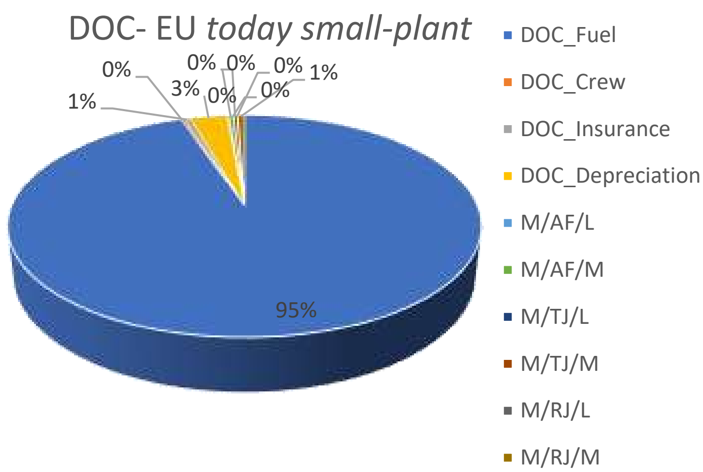


Figure 83: DOC for the LAPCAT A2 - today small-plant scenario EU

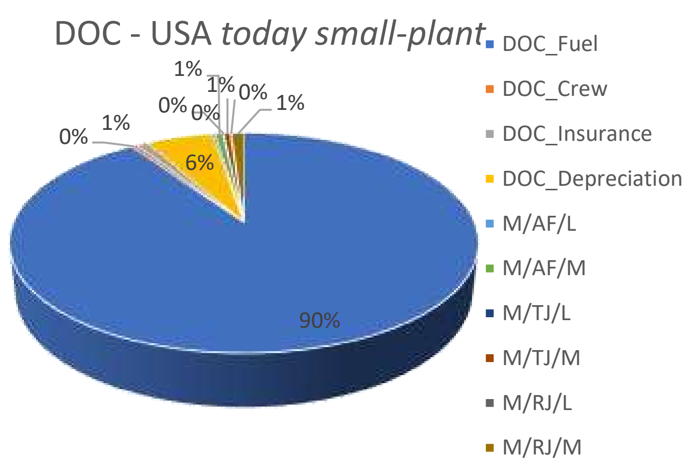


Figure 84:DOC for the LAPCAT A2 - today small-plant scenario USA

The only cost item that changes compared to the cost estimation of the section 7.3, for the USA the cost of fuel is the 90% of the total DOCs against the 95% of Europe.

In the case of today large plant the production rate is of 10 ton per day. The cost of fuel in the Europe is 8.73 $\$_{2017}$/kg (8.32 $\$_{2013}$/kg). In the USA, it is 5.10 $\$_{2017}$/kg (4.86 $\$_{2013}$/kg).

	EU		USA	
	$\$_{2017}$/bhr	**€$_{2013}$/bhr**	**$\$_{2017}$/bhr**	**€$_{2017}$/bhr**
DOC_Fuel	370464.27	389720.26	216401.00	227649.10
DOC_tot	401383.44	422246.54	247320.17	260175.38

Table 29: DOC for the LAPCAT A2 - today large plant scenario

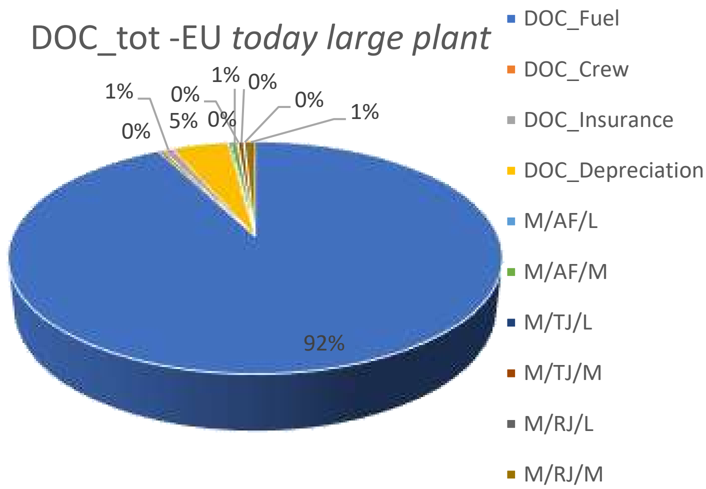


Figure 85: DOC for the LAPCAT A2 - today large plant scenario EU

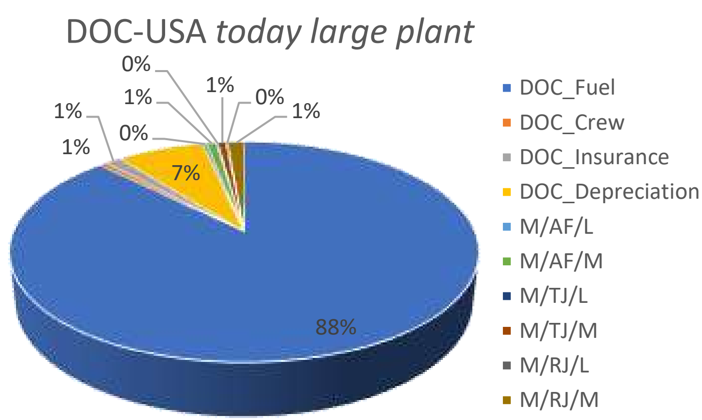


Figure 86: DOC for the LAPCAT A2 - today large plant scenario USA

The direct operating cost of fuel is greater in Europe than in the United States, where it is the 89% of the total DOCs.

The third productive scenario is called "Future Continuous". It corresponds to a production rate of 50 ton per day. In this case, the fuel price in Europe is 5.07 $\$_{2017}$/kg (4.83 $\$_{2013}$/kg) and in the USA, it 3.75 $\$_{2017}$/kg (3.57 $\$_{2013}$/kg). With the data of that productive scenario, it is done the cost estimation for the LAPCAT A2.

	EU		USA	
	$\$_{2017}$/bhr	€$_{2017}$/bhr	$\$_{2017}$/bhr	€$_{2017}$/bhr
DOC_Fuel	215065.20	226243.85	158961.23	167223.72
DOC_tot	245984.36	258770.14	189880.40	199750.00

Table 30: DOC for the LAPCAT A2 – Future continuous scenario

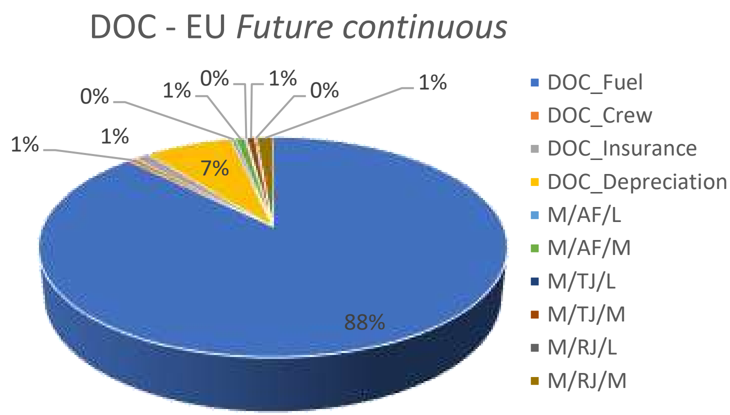


Figure 87:DOC for the LAPCAT A2 – Future continuous scenario EU

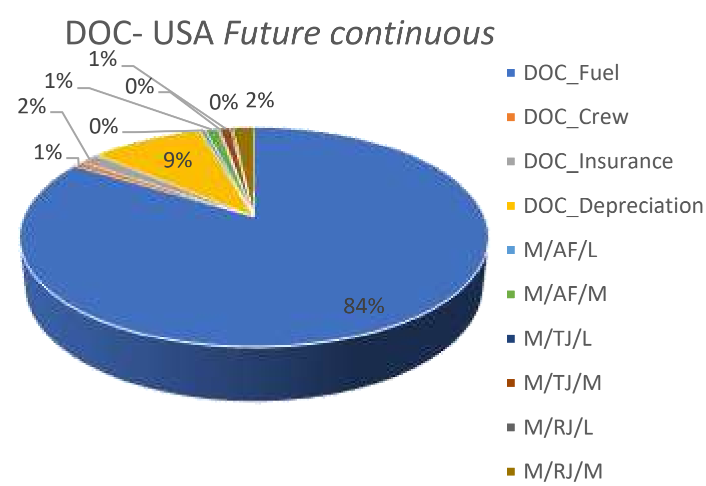


Figure 88: DOC for the LAPCAT A2 – Future continuous scenario USA

The DOC of liquid hydrogen is higher in Europe than in United States, where is the 88% of the total direct operating cost.

The last productive scenario is called “Future off-peak”. In this case, there are the maximum production rate, 200 ton per day, and the highest technological level of the plant. The cost of fuel in Europe is 3.26 $\$_{2017}$/kg (3.10 $\$_{2013}$/kg). In the USA, it is 2.91 $\$_{2017}$/kg (2.77 $\$_{2013}$/kg).

	EU		USA	
	$\$_{2017}$/bhr	€$_{2017}$/bhr	$\$_{2017}$/bhr	€$_{2017}$/bhr
DOC_Fuel	138033.56	145208.27	123339.67	129750.62
DOC_tot	168952.73	177734.55	154258.83	162276.90

Table 31: DOC for the LAPCAT A2 – Future off-peak scenario

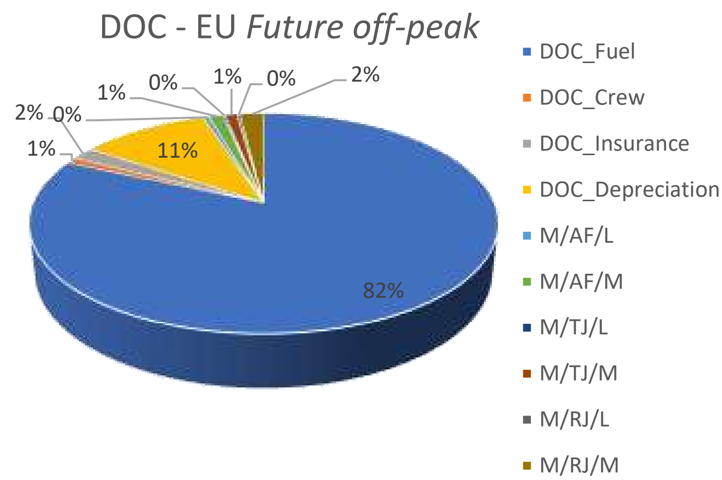


Figure 89:DOC for the LAPCAT A2 – Future off-peak scenario EU

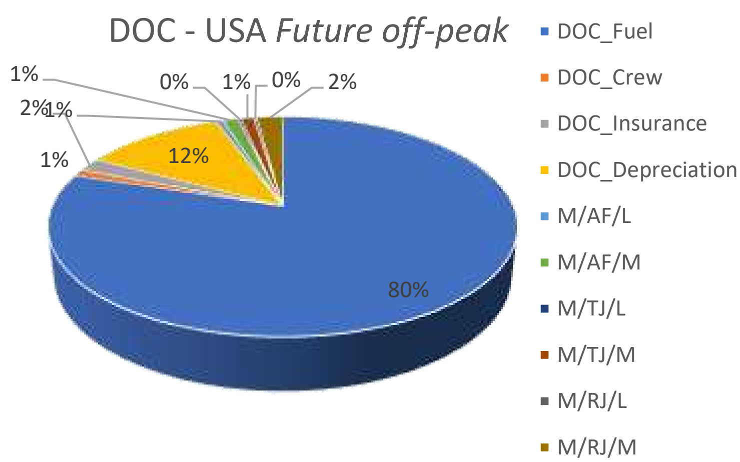


Figure 90: DOC for the LAPCAT A2 – Future off-peak scenario USA

The only operating cost that changes between the different operative scenario is the DOC of the fuel. Increasing the cost per unit of weight of fuel, the DOC grows too. The cost of fuel decreases with the increasing of the production rate. For the short-term scenarios, the difference between the fuel price per kilogram between the United States and the Europe is evident. In fact, the European cost of LH2 is about the double than the American one. The cost of energy changes a lot between countries. This is the main reason of the difference between the liquid hydrogen costs of two nations. In the case of the Europe, it is considered an average value between the energy costs of the different countries, because they have a different price for the energy. It is interesting to see that in the long-term productive scenarios, the difference of fuel costs between the USA and the EU is less, even if the American price is lower. The percentage of fuel cost decreases in the future scenarios. The depreciation cost tends to increase its value compared to all direct operating costs. The insurance cost has also the same trend, but its value does not overcome 2%. All the others cost items are less influential compared to the fuel costs and their changes are smallest than the other ones.

This analysis about the variation of the cost of the fuel is quite simple, because it does not consider the future variation of the market. On the other hand, it gives the possibility to evaluate the trend of the direct operating costs when their major cost item changes.

In *Figure 91*, it is possible compare the DOC of the fuel and the total direct operating costs of United States and Europe for different productive scenario of the LH2. It is interesting to see that in the "Future" scenarios, the DOC of fuel and the total direct operating costs of USA and Europe tend to be the same. This is due to the reduction of the cost per kilogram of liquid hydrogen.

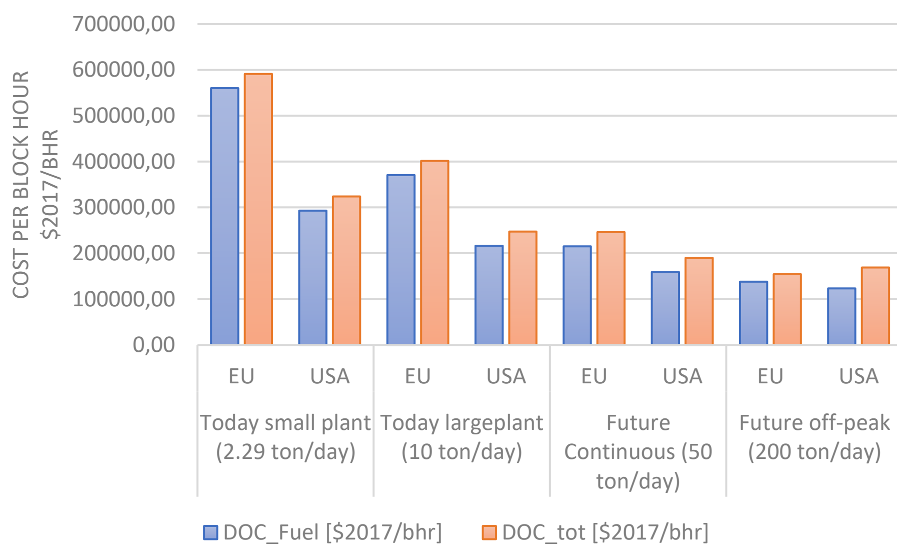


Figure 91: Comparison of the DOC od fuel and total direct operating costs between USA and EU for different productive scenarios of LH2.

7.4 Direct Operating Costs, Breguet formulation

The equations for the evaluation of the direct operating cost of fuel and of maintenance has been rewritten, introducing the Breguet formula of the range.

$$R = \frac{H}{g}\eta\frac{L}{D}\ln\left[\frac{1}{1-\frac{W_{fT}}{W_{GTO}}}\right] = \frac{V}{g\,sfc}\frac{L}{D}\ \ln\left[\frac{1}{1-\frac{W_{fT}}{W_{GTO}}}\right]$$

This new set of equations is interesting because it gives the possibility to evaluate the impact of the new hypersonic technologies on the direct operating costs. In the Breguet relationship, there are the specific fuel consumption and the aerodynamic efficiency. The first one is directly linked to the propulsive strategy, that is one of the main drivers in the project of a hypersonic aircraft. The second one is related to the aerodynamic performances and to the configuration of the aircraft. Increasing the flight speed, the drag coefficient grows too. The waverider configuration aims to increase the lifting coefficient using the additional lift generated by the shock waves.

For evaluating the specific fuel consumption of the LAPCAT A2, it is used reference [65] and reference [19]. They show that there is a relationship between the specific fuel consumption and the propulsive efficiency:

$$\eta = \frac{V_\infty}{sfc * H}$$

Where:

- η is the propulsive efficiency
- V_∞ is the flight velocity in [m/s]
- sfc is the specific fuel consumption in [kg/(s*N)]
- H is the fuel energy content in [J/kg]

Reference [16] suggests an approximated way to evaluate the propulsive efficiency; it is:

$$\eta = \frac{M_0}{M_0 + 3}$$

For the LAPCAT A2 the cruise Mach is 5. The propulsive efficiency is $\eta = \ 0.6250$. This value is confirmed by Table *32*

$\boldsymbol{M_\infty}$	0.9	2	4	6	8	10
$\boldsymbol{L/D_{max,euler}}$	17.3	10	7	6	5.5	5.2
$\boldsymbol{L/D_{max,viscous}}$	19.2	12	9	8	7.5	7.2
$\boldsymbol{\eta}$	0.25	0.4	0.57	0.67	0.73	0.77

Table 32: Aerodynamic L/D barrier and overall installed engine efficiency in function of flight Mach number [16].

$L/D_{max,euler}$ is the aerodynamic efficiency evaluated without considering the viscous effects. $L/D_{max,viscous}$, indeed, is the lift-to-drag ratio that takes into account the presence of the viscosity of the air.

Using the previous relationships, it has:

$$\eta = \frac{V_\infty}{sfc * H} \rightarrow sfc = \frac{V_\infty}{\eta * H}$$

The fuel energy content for the LH2 is about 130 MJ/kg, as suggested in the reference [65]. The specific fuel consumption for the LAPCAT A2 is:

$$sfc = \frac{V}{\eta * H} = 1.8158 * 10^{-5} \frac{kg}{N * s}$$

This value is obteined thanks to some approximated formulas. In reference [65], it is present the Figure 92. It shows an indicative value of specific fuel consumption for subsonic and hypersonic aircrafts as function of the non-dimensional range. The non-dimensional range is the ratio between the range of the aircraft and the ultimate anti-nodal point for a final destination, that is 20000 kilometers.

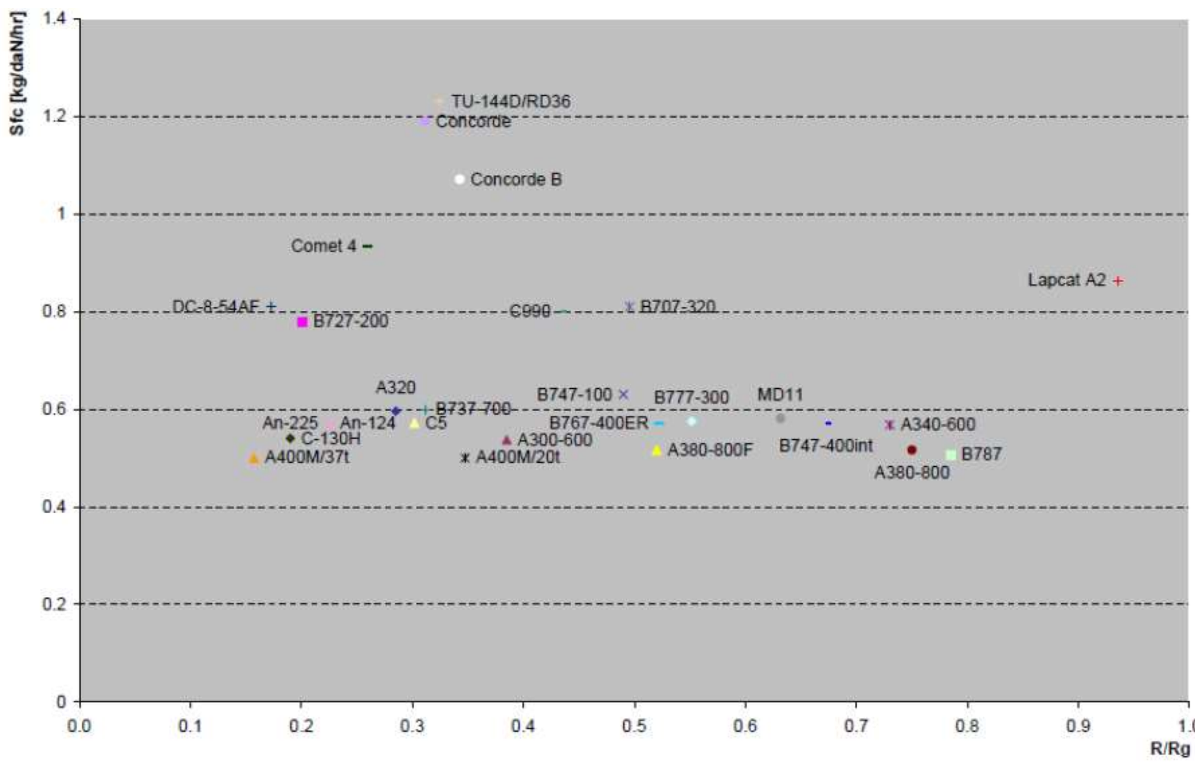


Figure 92: Indicative specific fuel consumption values for various sub- and supersonic aircraft in function [65].

From the Figure 92, it is possible to obtain the value of the specific fuel consumption for the LAPCAT A2. It is:

$$sfc = 0.88 \frac{kg}{daN * hr} = 2.4444 * 10^{-5} \frac{kg}{N * s}$$

It has the same order of magnitude of the specific fuel consumption evaluated with the approximated formulation.

The range evaluated with the Breguet equation is:

$$R = \frac{V_{cr}}{g\,sfc}\frac{L}{D}\ln\left[\frac{1}{1-\frac{W_{fT}}{W_{GTO}}}\right] = 2.5220 * 10^7\ m = 2.5220 * 10^4\ km$$

The inputs of the LAPCAT A2 direct operating costs estimation of the first section are used for the estimation of the range. The Breguet formula gives a greater value of the range than the references. This happens because the Breguet formulation of the range is an approximated equation for the evaluation of the cruise range. In fact, in the use of this relationship, there are the value of the maximum take-off weight and the weight at the landing. With the relationships $W_{landing} = W_{GTO} - W_{fT}$, it is possible to use the weight of fuel rather than the weight at the landing. It seems that all the fuel is used in cruise and at the landing there are not any reserve quantity. There is also the fact of all the other parameters are constant, even if they change during the flight.

The Breguet formula is used for the evaluation of the direct operating costs of fuel and of maintenance of the LAPCAT A2. According to reference [41], those cost items depend indirectly on the range of the aircraft. With the introduction of the Breguet formulation, it is possible to see the effect of the propulsive technologies and the aerodynamic configuration on the direct operating costs.

In Table *33*, there are the results obtained for the reference vehicle using the set of input of the previous estimation. The results are compared with the ones obtained from the application of the NASA cost estimation relationships.

	Breguet formulation		**NASA modified ATA CERs**	
	S/bhr	**€/bhr**	**S/bhr**	**€/bhr**
DOC Fuel	138580	145783.11	215065.20	226243.85
M/AF/L	680.84	716.23	809.26	851.32
M/AF/M	1274.50	1340.75	1815.33	1909.68
M/TJ/L	148.52	156.24	324.92	341.81
M/TJ/M	1041.10	1095.21	1615.07	1699.02
M/RJ/L	303.52	319.30	409.35	430.62
M/RJ/M	2841.50	2989.20	2222.10	2337.60
DOC Maintenance	6289.98	6616.92	7196.02	7570.06

Table 33: Direct Operating Costs of fuel and maintenance, using the Breguet equation of the range; Comparison with the previous cost estimation.

It is possible to see that the Direct Operating Costs evaluated with the Breguet formulation are lower than the ones of the NASA modified ATA CERs. This happens because the range evaluated with the equation is higher than the one the of the LAPCAT A2.

The Breguet equation permits to evaluate the cruise range of the aircraft. In the case of the hypersonic airplane, this phase is the longest one. Using this formulation, it is done an approximation. It is supposed to use all the fuel in the cruise phase increasing its range. In a hypersonic mission profile, there are some accelerations and decelerations, as in phase of take-off and landing. The mission profile is not the same of a subsonic jet because of the legislation rules and the necessities of the engines. The assumption to have a specific fuel consumption constant for all the time of flight is a great approximation. Despite those aspects, the formulation that uses the Breguet equations gives costs of the same order of magnitude of the NASA modified ATA CERs. These new equations can be corrected using a corrective factor. They can give the possibility to evaluate directly how a change in the propulsion strategy or in the structure configuration can have effect on the direct operating costs.

To have the same range of Table *18*, the specific fuel consumption should be:

$$sfc = \frac{V}{g\,R}\frac{L}{D}\,\ln\left[\frac{1}{1-\frac{W_{fT}}{W}}\right] = 3.2967 * 10^{-5}\,\frac{kg}{N*s}$$

This value is higher than the one obteined by Figure 92, because the refernce range is lower.

From the Breguet equation, it is possible to obtain the ratio between the fuel weight and the maximum take-off weight and the aerodynamic efficiency. Those terms are very important in the equation of the direct oprative cost of the fuel and in the equation of the direct operating cost of mainteance labor of the ramjet rispectively. They are:

$$R = \frac{V}{g*sfc}\left(\frac{L}{D}\right)\ln\left[\frac{1}{1-\frac{W_{fT}}{W_{GTO}}}\right] \rightarrow \frac{W_{fT}}{W_{GTO}} = 1-\frac{1}{\exp\left(\frac{R*g*sfc}{V*\left(\frac{L}{D}\right)}\right)}$$

$$R = \frac{V}{g*sfc}\left(\frac{L}{D}\right)\ln\left[\frac{1}{1-\frac{W_{fT}}{W_{GTO}}}\right] \rightarrow \frac{L}{D} = \frac{R*g*sfc}{V*\ln\left[\frac{1}{1-\frac{W_{fT}}{W_{GTO}}}\right]}$$

Using the specific fuel consumption obtained from the Figure 92 ($sfc = 0.88\,\frac{kg}{daN*hr} = 2.4444 * 10^{-5}\,\frac{kg}{N*s}$), the following values of the weights ratio and for the aerodynamic efficiency are obtained:

$\boldsymbol{\frac{W_{fT}}{W_{GTO}}}$	0.3974
$\boldsymbol{\frac{L}{D}}$	4.4489

Table 34: Ratio between the fuel weight and the maximum take-off weight and the aerodynamic efficiency using the Breguet equation

From the data of the LAPCAT A2, it has that the aerodynamic efficiency is 6 and the ratio of the weight is 0.495. The values obtained with the Breguet formulation are lower than the ones suggested by the references. This is due to the approximation made by this formulation, as the evaluation only of the cruise range and the fact of the specific fuel consumption is constant.

Using those data are for the evaluation of the direct operating cost of the fuel and of the labor maintenance of the ramjet, it has the value in the Table *35*.

	Breguet formulation		NASA modified ATA CERs	
	S/bhr	**€/bhr**	**S/bhr**	**€/bhr**
DOC Fuel	150060.00	157859.82	215065.20	226243.85
M/RJ/L	498.32	524.22	409.35	430.62

Table 35: Direct Operating Costs of fuel and maintenance labor of the ramjet, using the Breguet equation of the range; Comparison with the previous cost estimation.

The values of the first two columns of Table 35 are greater than the ones of the Table 33. They are closer to the cost of the NASA method estimation. It is interesting to see that the cost of the maintenance of the ramjet is greater than the one obtained by using the equation of the reference [41].

As said before the Breguet equation of the range is an approximate way to evaluate the cruise range of the subsonic aircraft. Its introduction in the CERs for the direct operating cost evaluation is very important, because it give the possibility to understand the impact of new technologies, in particular the propulsive and the aerodynamic ones, on the direct operating costs. This can help both the designer and the costumer to develop a product that could be cost-effective and gives great profit, because they can choose the technological features that can gives advantage both under the performances and the economic point of view.

8. Conclusions

The objectives of this work are to analyze the direct operating cost of a hypersonic point-to-point vehicle and to evaluate the impact of the technological drivers on the DOCs of a hypersonic point-to-point vehicle.

At the beginning, the life cycle costs of aircraft are analyzed. After that there is a brief discussion about the hypersonic field. It is shown the LAPCAT project and the reference vehicle for the cost estimation, the LAPCAT A2. There is the comparison between different mathematical methods for the cost analysis. They come from the aeronautical and the space field. The method used for the direct operating cost evaluation of a hypersonic point-to-point vehicle was developed by NASA in 1972 [41]. It come from a model studied by the ATA [1], that gave useful results for the cost estimation of subsonic and sonic vehicle. To truly understand the impact of the new technologies on the direct operating costs, the NASA equations are analyzed in detail. The DOCs are divided into cost of fuel, cost of crew, cost of insurance, cost of depreciation and cost of maintenance. The relationships between the new technologies and the equations' terms are defined. It is possible to see that the most interesting equations under a technological point of view are the one of the direct operating cost of fuel and the one of direct operating cost of maintenance. It is suggested an alternative formulation of these two equations, using the aeronautical equation of Breguet [19]. This relationship permits to evaluate the cruise range using some quantities related to technological features of the hypersonic vehicle. It gives the possibility to evaluate the impact of the propulsive strategies (described by the specific fuel consumption) and of the configuration (represented by the aerodynamic efficiency) on the direct operating costs. These two aspects are very relevant in the case of hypersonic aircraft. The equations of the insurance and depreciation are rewritten considering the effect of some vehicle's characteristics on the acquisition costs, because they are directly dependent on the price of the vehicle. After that, it is shown the MATLAB program developed to evaluate the DOCs. It uses the equation of the NASA methodology [41]. In the last part there is the evaluation of the costs for the LAPCAT A2. The results obtained are consistent with that has been said by the data from the literature [19]. The most relevant cost item in the case of hypersonic vehicle is the cost of fuel. The results of the equations obtained using the Breguet formulas are compared to the ones obtained using the NASA method.

This work shows how important it is to have the right cost estimation for a hypersonic aircraft because its direct operating costs are too high. This is not easy because there are not hypersonic vehicles on service and the comparison with a subsonic jet is wrong. The statistical population is poor and the only method to evaluate operating costs is the CERs. For the evaluation of the impact of new technologies on the direct operating costs, most experimental data are necessary. It is difficult to develop new relationships without a comparison. The data available for the subsonic aircraft cannot be always used.

Considering that, the thesis is focused on the impact of the technological drivers on the direct operating costs, because it is important to evaluate the effect of the different drivers on the DOCs before developing a new mathematical model. Under a technological point of view, the propulsive system and the configuration of the vehicle have a great impact on the direct operating cost of a hypersonic point-to-point vehicle. They should be considered for the developing of new set of mathematical relationships for the

DOCs evaluation. For that reason, it is exploited into the NASA modified ATA CERs [41] the Breguet formula of the range. It is a basic formula for the evaluations of the cruise range of subsonic aircraft. This is a simple way to rewrite the direct operating costs equations, but it gives the possibility to explain the drivers linked directly to technologies of the vehicle. The results obtained using the Breguet formulas of the range are different from the ones that come from the CERs of the NASA method [41]. This has been predictable, considering the simplifications introduced by that relationships. On the other hand, it should be underlined that the results have the same order of magnitude and are comparable. The introduction of a corrective factor can be useful for having the same value of the DOCs between the different sets of CERs. Another important aspect is the fact of the data introduced in the formulation are not precise. This is the case of the specific fuel consumption of the Scimitar engine, that should be evaluated better in the testing phase. The use of the Breguet formulation in the NASA equations gives the possibility to evaluate clearly the effect of the propulsive strategy and of the configuration on the DOCs. This is useful in the design phase, because an economic feedback can help the designers to define the best structure of the vehicle.

The MATLAB tool gives the possibility to do the direct operating costs estimation rapidly, because it is based on the use of graphical user interfaces that help even the not-expert users. The fact of saving the inputs and the results on an Excel document gives the possibility to export and to analyze data using other pre/post processing programs.

The future development of the thesis can be the followings:

- Starting from the results obtained by the introduction of the Breguet formula into the NASA CERs, the use of more precise data for having the same results for all different formulations. The Breguet formula evaluates only the cruise range. It could be useful to estimate also the contribution of the initial and final phases of the flight.
- A better comparison between the results obtained with the NASA CERs and the one of the equations that use the Breguet formulation, for evaluating which equations describe more clearly the hypersonic case. It is possible to use both of them to reach a result that is the most detailed as possible.
- The evaluation of the impact of the drivers on the direct operating costs using the formulation with the Breguet equations. It will be possible to see the variation of the direct operating cost when an input, as the propulsive configuration, will change.
  In this thesis, the only one driver that is changed is the cost of the fuel. It is interesting to analyze the variation of the DOC at the changes of other parameters. The drivers can be modified one at time or different combinations can be tested, to better understand the trend of the direct operating costs.
- The study and the development of a new set of mathematical relationships for the estimation of the direct operating cost of a hypersonic point-to-point vehicle.
  The new CERs can be different from the NASA equations developed in the 1972. This is a difficult point, because there are few data for the hypersonic aircraft. The use of the results of the NASA equations and the introduction of the Breguet formulation can give the possibility to evaluate the trends of the DOCs and to write new mathematical relationships thanks to the previous results.
- The development of complete tool for the evaluation of the all life cycle costs of hypersonic point-to-point vehicle.

The program developed is set for the introduction of other mathematical model for the evaluation of the items of the LCCS. The tool should be easy to use and it should require data available at the beginning phase of the project. It should also be precise, avoiding mistakes in the evaluation. Developing a proper section, it should permit evaluate the impact of the technological features in the all lifecycle costs. A further detail can be the possibility to select the kind of mission of the aircraft. This detail turns the program and it will be possible the estimation of the life cycle costs of all types of hypersonic aircrafts. It is important that it can use a worksheet to save the input and the results, giving the possibility to use other program for the pre/post processing of the data.

REFERENCES

[1] ATA, «Standard Method of Estimating Comparative Direct Operating Cost of Turbine Powered Transport Airplane,» 1967.

[2] E. M. Repic, G. A. Olson e R. J. Milliken, «A methodology for hypersonic transport technology planning,» NASA, Downey, 1973.

[3] J. Roskam, Airplanne Design, Ottawa, Kensas : Roskam Aviation and Engineering Corporation , 1985.

[4] N. Viola, M. Fioriti, L. Boggero, D. Ferretto e R. Fusaro, *Slide of the course of "Progetto di sitemi earospaziali Integrati",* 2016-2017.

[5] D. P. Raymer, Aircraft Design: A Conceptual Approach, Fifth Edition, merican Institute of Aeronautics and Astronautics, 2012.

[6] L. R. Jenkinson, P. Simpkin e D. Rhodes, Civil Jet Aircraft Design, Butterworth - Heinemann, 1999.

[7] NASA, NASA Cost Estimating Handbook, 2008.

[8] Office of the Under Secretary of Defense for Acquisition, Technology and Loistics;, «OUSD(AT&L),» [Online]. Available: https://www.acq.osd.mil.

[9] ICAO, «Safety REPORT 2017,» ICAO, 2017.

[10 «www.statista.com,» [Online].

[11 IATA, «Airline Disclosure Guide: Aircraft acquisition cost and depreciation».

[12 M. Dixon, «The Maintenance Costs of Aging Aircraft. Insights from Commercial,» RAND PROJECT AIR FORCE, 2016.

[13 J. J. Lee, S. P. Lukachko, I. A. Waitz e A. Schafer, «HISTORICAL AND FUTURE TRENDS IN AIRCRAFT PERFORMANCE, COST, AND EMISSIONS,» *Annual Reviews Energy Environment,* n. 26, pp. 167-200, 2001.

[14 IATA, «IATA,» [Online]. Available: http://www.iata.org.

[15 M. I. o. Technology, «Emplyoees Compensation,» 2013.

[16 J. Roskam, Airplane Design, Ottawa: Roskam Aviation and Engineering Corporation, 1985.

[17 M. Repic, G. A. Olson e R. J. Milliken, A methodology for hypersonic, NASA, 1973.

[18 D. E. Koelle, Handbook of the Cost Engineering for Space Transportation System with TRANSCOST, 2011.

[19 J. Steelant, «LAPCAT: High-Speed Propulsion Technology».

[20 M. Sippel, T. Schwanekamp, O. Trivalio, A. Kropp, C. Bauer e N. Garbers, «SpaceLiner Technical Progress and Mission Definition,» in *20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, Glasgow, 2015.

[21 ICAO, *ICAO Long-Term Traffic Forecasts (Passenger and Cargo),* 2016.

[22 V. D'Oraino, *Aerodynamic study of a small hypersonic plane.*

[23 European Space Agengy, «Parabolic flights,» [Online]. Available: http://wsn.spaceflight.esa.int/docs/EUG2LGPr3/EUG2LGPr3-5-ParabolicFlights.pdf.

[24 T. Langener, S. Erb e J. Steelant, «TRAJECTORY SIMULATION AND OPTIMIZATION OF THE LAPCAT-MR2 HYPERSONIC CRUISER CONCEPT,» in *29th Congress of the International Council of the Aeronautical Sciences*, St. Petersburg, 2014.

[25 E. Sanger e B. J, «A ROCKET DRIVE FOR A LONG RANGE BOMBER,» TECHNICAL INFORMATION BRANCH BUAER NAVY DEPARTMENT , 1944.

[26 D. R. Jenkins, T. Landis e J. Miller , AMERICAN X-VEHICLES An Inventory—X-1 to X-50, Washington DC : National Aeronautics and Space Administration, 2003.

[27 NASA, «NASA Armstrong Fact Sheet: XB-70 Valkyrie,» 1 Marzo 2014. [Online]. Available: https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-084-DFRC.html.

[28 «X-33/VentureStar – What really happened,» [Online]. Available: https://www.nasaspaceflight.com.

[29 M. Hempsell e R. Longstaff, «SKYLON USERS'MANUAL,» Reaction Engines Ltd , Abingdon, 2009.

[30 M. Sippel, O. Trivalio, B. L e V. C, «Evolution of the SpaceLiner towards a Reusable TSTO-Launcher,» in *International Astronautical Congress 2016*, Guadalajara, 2016.

[31 J. Steelant, A. Bond, A. Götz, C. Bruno e J. Longo, «LAPCAT Long-Term Advanced Propulsion Concepts and Technologies Final Activity Report,» 2008.

[32 J. Steelant e M. van Duijn2, «Structural Analysis of the LAPCAT-MR2 Waverider Based Vehicle,» in *17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, San Francisco, California, 2011.

[33 ESA. [Online]. Available: http://www.esa.int/Our_Activities/Space_Engineering_Technology/LAPCAT_II.

[34 j. Steelant, «LAPCAT Long-Term Advanced Propulsion Concepts and Technologies SPECIFIC TARGETED RESEARCH PROJECT,» 2008.

[35 J. Steelant e T. Langener, «THE LAPCAT - MR2 HYPERSONIC CRUISER CONCEPT,» in *29th Congress of the Intenational Councilof the Aeronautical Sciences*, St. Petersburg, 2014.

[36 J. Steelant, «LAPCAT: High-Speed Propulsion Technology».

[37 V. F. Villace e J. Steelant, «The Thermal Paradox of Hypersonic Cruisers,» in *20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, Glasgow, 2015.

[38 F. Jivraj, R. Varvill, A. Bond e G. Paniagua, «The Scimitar Precooled Mach 5 Engine,» in *2ND EUROPEAN CONFERENCE FOR AEROSPACE SCIENCES (EUCASS)*.

[39 MIT, «AIRLINE DATA PROJECT,» [Online]. Available: http://web.mit.edu/airlinedata/www/default.html.

[40 C. R. McClinton, «High Speed/Hypersonic Aircraft Propulsion Technology Development,» NATO.

[41 Repic, E. M., G. Olson e R. J. Milliken, «METHODOLOGY FOR HYPERSONIC TRANSPORT TECHNOLOGY PLANNING,» NASA , Downey, 1973.

[42 International Energy Agency, «Hydrogen production and Storage - R&D Priorities and Gaps,» OECD/IEA, Parigi, 2006.

[43 P. Nekså e D. Berstad, *Sites and concepts for possible hydrogen production and export from Norway,* Tokyo: SINTEF, 2015.

[44 Ausralian Government Civil Aviation Safety Autority, «GUIDELINES FOR AIRCRAFT FUEL REQUIREMENTS,» Civil Aviation Advisory Publication , 2006.

[45 E. Torenbeek, Optimum Cruise Performance of Subsoni Transport Aircraf, Delft: Delft University Press, 1998.

[46 W. Yu, S. Hong e Z. Peiwen, «Aircraft trip DOC parameters: A function of stage length, seat capacity and design range,» in *International Conference on Industrial Engineering and Engineering Management*, Hong Kong, 2012.

[47 ICAO, «Operation of Aircraft Annex 6,» ICAO, 2013.

[48 U. Cardella, L. Decker e H. Klein, «Economically viable large-scale hydrogen liquefaction,» IOP Conf. Series: Materials Science and Engineering, 2017.

[49 D. E. Koelle, Handbook of Cost Engineering and Design of Space Transportation Systems, Revision 4b ed. , 2013.

[50 K. Grave, B. Breitschopf, J. Ordonez, J. Wachsmuth, S. boeve, M. Smith, T. Schubert, N. Friedrichsen, A. Herbst, K. Eckartz, M. Pudlik, M. Bons, M. Ragwitz e J. Schleich, «Price and cost of EU energy,» European Commission , 2006.

[51 Calculator US Inflation, «Consumer Price Index Data from 1913 to 2018,» [Online]. Available: http://www.usinflationcalculator.com/inflation/consumer-price-index-and-annual-percent-changes-from-1913-to-2008/.

[52 T. Nobe, «A fuselage/tank structure study for actively cooled hypersonic cruise vehicles.,» McDonnell Dougas Corporation, St. Louis, 1975.

[53 NDP Solutions, «Custumer-Focused Development with QFD,» [Online]. Available: http://www.npd-solutions.com/qfd.html.

[54 S. Ackert, «Engine Maintenance Concepts for Financiers - Elements of Turbofan Shop Maintenance Costs,» Aircraft Monitor2, 2011.

[55 W. Mason, *Supersonic Aerodynamics,* 2016, pp. 1-72.

[56 ATA, «Standard Method of Estimating Comparative Direct Operating Cost of Turbine Powered Transport Airplane,» 1967.

[57 [Online]. Available: https://www.statista.com/statistics/244983/projected-inflation-rate-in-the-united-states/.

[58 U. I. Calculator, «Consumer Price Index Data from 1913 to 2018,» [Online]. Available: http://www.usinflationcalculator.com/inflation/consumer-price-index-and-annual-percent-changes-from-1913-to-2008/.

[59 M.-. M. I. o. Technology, «AIRLINE DATA PROJECT,» [Online]. Available: http://web.mit.edu/airlinedata/www/Employees&Compensation.html.

[60 C. A. S. AUTHORITY, «STANDARD PASSENGER AND BAGGAGE WEIGHTS,» 1990.

[61 J. P. Weinder, «Conceptual Study of a Turbojet/Ramjet Inlet,» NASA, Hampton, 1979.

[62 J. Steelant e M. van Duijn, «Structural Analysis of the LAPCAT-MR2 Waverider Based Vehicle,» in *17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, San Francisco, California, 2011.

[63 R. E. Limited., *LAPCAT A2 Facts and Figures,* 2008.

[64 FAA, «AIRCRAFT OPERATING COSTS,» [Online]. Available: https://www.faa.gov/regulations_policies/policy_guidance/benefit_cost/media/econ-value-section-4-op-costs.pdf.

[65 J. Steelant, «Hypersonic Technology Developments with EU Co-Funded Projects,» NATO.

[66 N. Viola, M. Fioriti, L. Boggero, D. Ferretto e R. Fusaro, *Slidedof the course of "Progetto di sitemi earospaziali Integrati",* 2016-2017.

[67 Wikipedia.. [Online]. Available: www.wikipedia.com.

[68 esa, «Achivement obteined within the european LAPCAT program,» [Online]. Available: http://www.esa.int/Our_Activities/Space_Engineering_Technology/Achievements_obtained_within_the_European_LAPCAT_program.

[69 I. E. Agency, «Hydrogen production and Storage - R&D Priorities and Gaps,» 2006.

[70 S. Balland, V. F. Villace e J. Steelant, «Thermal and Energy Management for Hypersonic Cruise Vehicles – Cycle Analysis,» in *International Space Planes and Hypersonic Systems and Technologies Conferences*, Glasgow, 2015.

[71 T. Cain, «Ramjet Intakes,» NATO.

[72 M. Willard e D. Giel, «Scramjet/Ramjet Design and Integration Trade Studies Using SRHEAT™,» in *45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Denver, 2009.

[73 Airforce research laboratory, «PROPULSION DIRECTORATE Monthly Accomplishment Report,» 2005.