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Analysis of Direct Operating Costs estimation of a Supersonic point-to-point vehicle powered by liquid hydrogen

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Abbreviation

(1)	DOC	Direct Operating Cost
(2)	IOC	Indirect Operating Cost
(3)	TOC	Total Operating Cost
(4)	LCC	Life Cicle Cost
(5)	WLCC	Whole Life Cicle Cost
(6)	RDTE	Research, Development, Test & Evaluation
(7)	WBS	Work Breakdown Structure
(8)	CERs	Cost Estimating Relationships
(9)	NASA	National Aeronautics and Space Administration
(10)	ATA	Air Transport Association of America
(11)	ICAO	International Civil Aviation Organization
(12)	IATA	International Air Transport Association
(13)	FAA	Federal Aviation Administration
(14)	ESA	European Space Agency
(15)	IEA	International Energy Agency
(16)	MIT	Massachusetts Institute of Technology
(17)	CS	Certification Specification
(18)	SST	Supersonic Cruise Transport
(19)	HST	High speed Transport
(20)	RPK	Revenue Passenger Kilometres
(21)	ASK	Available Seat Kilometres
(22)	USD	United States Dollars
(23)	CPI	Consumer Price Index
(24)	CEF	Cost Escalation Factor
(25)	F.Y.	Fiscal Year
(26)	TP	Technological Parameters
(27)	LH2	Liquid Hydrogen
(28)	CAPEX	CAPital EXpenditures
(29)	OPEX	OPerating EXpenditures
(30)	EEX	Electricity Expenditures
(31)	TLC	Total Liquefaction Cost
(32)	LCOH	Levelized Cost of Hydrogen

(33)	bhr	Block Hours
(34)	ISA	International Standard Atmosphere
(35)	MTOW	Maximum Take-Off Weight
(36)	SFC	Specific Fuel Consumption
(37)	FL	Flight Level
(38)	TBO	Time Between Overhaul

Abstract

This thesis work focuses on the analysis of the direct operating costs of a supersonic civil transport aircraft powered by liquid hydrogen.
As we know, the correct assessment of direct operating costs from the early stages of an aircraft project is of primary importance.
This assessment, however, is neither easy nor immediate, given that its accurate estimation requires the use of a substantial database, which it is not possible to use in the case of supersonic aircraft seen the few real aircraft to refer to and by the not always accurate comparison with data from subsonic aircraft. In addition to this, it is also necessary to analyzed the impact that a new technology such as liquid hydrogen (a technology widely studied and debated and that will certainly be used on aircraft in the coming decades) has on costs.
On the basis of this it is therefore necessary to develop and use a mathematical model of estimation of the costs that can be applied even when only a few data concerning the physical characteristics/ performance of the aircraft are defined, the mission to be carried out and the economic scenario.
For this reason, the thesis work has as a starting point the mathematical model for the estimation of costs developed by NASA in 1973 [2] on which will be conducted appropriate analysis in order to be able to obtain a new updated model of cost estimation more in line with current times.
In order to obtain clear information on the work carried out, as a first step, the typical life stages of an aerospace product will be illustrated and for each phase will be briefly described the cost items that characterize them. Subsequently, some historical and reference aspects will be reported regarding supersonic aircraft powered by traditional fuel and liquid hydrogen. In the latter case we will focus in particular on introducing the characteristics of GREEN CONCORDE [7], aircraft developed in advance during the course of "design of integrated aerospace systems" during the academic year 2019-2020 at the Polytechnic of Turin that will be used as a reference for the development of the case study.
It will then be illustrated the mathematical model of estimation of direct operating costs developed by NASA on an ATA [2] basis, which will serve as a basis for the realization of the new model of estimation. So, for each item present within the equations of the model will be conducted where necessary an in-depth analysis with the aim of updating the relevant CERs (Cost Estimation Relationships) so that the latter can provide estimation values that are more in line with current market values.
Thanks to the implementation of the new estimation model within a MATLAB script will be seen is analysed what are the results obtained from the case study referring to GREEN CONCORDE [7]and its typical mission. They will be therefore shown and analysed what are the relative direct costs in terms of $/block hours and the breakdowns of the various cost items within the DOC reporting the reasons that have led to those specific values.
Subsequently, in order to validate these results and the model itself, different comparisons will be made, starting from the values obtained by the NASA model [2] of departure (executed in a second script always with the same input values), to continue with the comparison with other categories of aeroplanes, with the current

values of marker and finally compared to other possible future scenarios that significantly change the cost of fuel.
Finally, for the sake of completeness of the activities, a method for the estimation of indirect operating costs to estimate the total operating cost per flight will be reported and thus be able to obtain a first price of the air ticket and assess in advance how the latter is positioned on the market compared to the current carriers of line.

Abstract - ITA

Questo lavoro di tesi ha come oggetto l'analisi dei costi operativi diretti inerenti ad un velivolo di trasporto civile supersonico alimentati ad idrogeno liquido.
Come sappiamo la corretta valutazione dei costi operativi diretti già dalle prime fasi di un progetto aereospaziale risulta essere di primaria importanza, tuttavia questa non risulta essere né facile né tanto meno immediata, dato che una sua stima accurata richiede l'utilizzo di una base di dati corposa non sempre reperibile (specie per i velivoli supersonici). Oltre a questo è necessario andare ad analizzare anche l'impatto che una nuova tecnologia come quella dell'idrogeno liquido (tecnologia ampiamente studiata e dibattuta e che verrà sicuramente impiegata sui velivoli nei prossimi decenni) ha sui costi.
Sulla base di questo dunque è necessario sviluppare e utilizzare un modello matematico di stima dei costi che possa essere applicato anche quando sono definiti solo pochi dati riguardanti le caratteristiche fisiche/prestazionali del velivolo, della missione da svolger e dello scenario economico.
Per questo il lavoro di tesi ha come punto di partenza il modello matematico per la stima dei costi sviluppato dalla NASA nel 1973 [2] sulla quale verranno condotte delle opportune analisi con il fine di riuscire ad ottenere un nuovo modello aggiornato di stima dei costi maggiormente in linea con i tempi correnti.
Per riuscire dunque ad avere delle informazioni chiare sul lavoro svolto, come primo step, saranno illustrate le tipiche fasi di vita di un prodotto aerospaziale e per ogni fase verranno brevemente descritte le voci di costo che le caratterizzano. Successivamente saranno riportati alcuni aspetti storici e di riferimento riguardante i velivoli supersonici alimentati a combustibile tradizionale e ad idrogeno liquido. In quest'ultimo, caso ci si soffermerà in particolare sull'introdurre le caratteristiche del GREEN CONCORDE [7], velivolo sviluppato in via preliminare durante il corso di "progettazione dei sistemi aerospaziali integrati" durante l'anno accademico 2019-2020 presso il Politecnico di Torino che verrà usato come riferimento per lo sviluppo del caso di studio.
Verrà successivamente illustrato il modello matematico di stima dei costi operativi diretti sviluppato dalla NASA su base ATA [2], che fungerà da base di partenza per la realizzazione del nuovo modello di stima. Quindi, per ogni voce presente all'interno delle equazioni del modello verrà condotta là dove necessario un'analisi approfondita con il fine di aggiornare le relative CERs (Cost Estimation Relationships) in modo che quest'ultime riescano a fornire dei valori di stima più in line con gli attuali valori di mercato.
Grazie all'implementazione del nuovo modello di stima all'interno di uno script MATLAB saranno visti è analizzati quelli che sono i risultati ottenuti dal caso di studio facente riferimento al GREEN CONCORDE [7] e alla sua tipica missione. Verranno dunque mostrati ed analizzati quelli che sono i relativi costi diretti in termini di $/block hours e le ripartizioni delle varie voci di costo all'interno dei Direct Operative Cost riportando le motivazioni che hanno portato a quei specifici valori.
Successivamente, con il fine di validare tali risultati e il modello stesso, saranno eseguiti diversi confronti, a cominciare dai valori ottenuti dal modello NASA [2] di partenza (eseguito in un secondo script sempre con gli stessi valori di input), per proseguire con il confronto con altre categorie di velivoli, con i valori attuali di

marcato ed infine rispetto ad altri possibili futuri scenari che vanno a modificare notevolmente il costo del carburante.
Per completezza delle attività, sarà riportato un metodo per la stima dei costi operativi indiretti per valutare il costo operativo totale per volo e cosi riuscire a stimare il prezzo del biglietto aereo e valutare in via preliminare come quest'ultimo si posiziona sul mercato rispetto gli attuali vettori di linea.

1. Introduction

1.1. Ecological aspect

As we know, the use of liquid hydrogen as an energy source in order to reduce some of the world's environmental pollution is one of the biggest challenges in the world in all sectors.
In 2020, it was estimated that the aerospace industry emits more than 900 million tons of CO2 annually.
Given the growth of the aerospace sector and also its resilience to global crises, the sector is expected to have continuous growth of 3-4% per year. Despite the possible improvements in efficiency that can be introduced over the years, CO2 emissions from the sector are expected to double by 2050.
In order to reduce total CO2 emissions as much as possible, several actors from different sectors are carrying out numerous studies, among which those related to the adoption of hydrogen as a primary source of energy stand out.
As far as aerospace is concerned, the use of hydrogen as a primary source of propellant could reduce combustion-related CO2 emissions by 100% and thus reduce the environmental impact of flights for between 50 and 75%.
The adoption of this energy source, however, requires a great deal of effort in terms of research and development, investment and correct regulation.
In the aerospace field, the different projects related to the use of hydrogen vary both in the different configurations of aircraft and for different mission profiles, thus adapting both to the small propeller aircraft, ideal for short-range flights in which studies carried out prefer the use of hydrogen fuel cells, up to the much more ambitious projects of hypersonic aircraft powered by liquid hydrogen, able to connect city to the antipodes of the globe in a few hours of mission.
Economic feasibility analysis conducted in recent years by McKinsey & Company for the Clean Sky 2 [3], shows how in the future most of aviation will adopt a mix of solutions related to this technology.

1.2. Historical aspect

Historically, the first studies of the use of liquid hydrogen on supersonic aircraft date back to the mid-1970s when Boeing was working on the design of its 2707 model, set aside eventually for economic reasons.
As is well known, to date, the only examples of supersonic civil transport aircraft to have crossed our skies are the CONCORDE and TUPOLEV TU-144. Machines that are simply technologically exceptional, especially in relation to the years of design and manufacture, but which have not enjoyed the same reputation in terms of costs. In fact, one of the reasons for the closure of these ambitious projects is mainly related to the exorbitant operating costs that these means had to bear during their operational life.

Nowadays, given the advancement of technology, production capabilities and design methodologies, a partial reduction of cost drives could be observed for this type of aircraft, that evaluated together with the increase in global per-capita wealth could lead stakeholders to have a new possible interest in their adoption, going to re-occupy market segments exclusively covered by subsonic aircraft.

However, for this to happen, it is necessary for the aircraft to be not only economically feasible but also economically viable.
Convenience is necessary so that all the stakeholders who finance the project (public and private bodies), have an appropriate economic return according to their usage plan.

1.3. Economic aspect

When an airline decides to buy a new aircraft, in fact, it does so by taking more account of the costs of maintaining the operating aircraft. These costs are considerable and can easily exceed the costs related to the acquisition of the aircraft. For this reason, it is extremely important that the operating costs are as low as possible, in order to increase not only the profits of designers and manufacturers but above all to minimize the expenses that airlines will have to bear during the use of the vehicle in order to maximize cost-effectiveness (Index that represents the degree of satisfaction of an aerospace product going to relate all performance parameters with the total cost of the aircraft throughout its life).
It is of paramount importance that these operating costs are calculated from the earliest stages of design, completing what is the evaluation of the life cycle cost, representing all the items within the various stages of the life of an aerospace program from the initial stages of the design until its disposal.
During the initial design phase, despite the lack of data available, it will be extremely important to go and evaluate through the use of mathematical models based on cost evaluation relationships (CERs) what is the impact of the various drivers on the cost of the aircraft, in order to make an initial estimate of the costs and evaluate which of the different configurations that can be adopted on an aircraft can be successful on the market in terms of economic.

1.4. Methodology

To date, there are several models developed by various bodies in order to make an initial estimate of operating costs. Among these certainly the best known is important method for estimating direct operating costs was developed by ATA [1] in 1967 [1]. In 1973, NASA [2] modified this model by generating one with a series of equations for assessing the direct operating costs for a high-speed aircraft operating a point-to-point mission.
In this work, it was decided to use initially the NASA model [2] how base to evaluate the DOC of Green Concorde [7].
This model has been carefully studied in order to understand the impact of the various cost drivers.
Following, the NASA cost estimation relationships [2] will be rewritten, suggesting possible alternative formulas, which would take into account the effect of changes due to the adoption of technologies consolidate to a supersonic aircraft powered by liquid hydrogen.
However, it must be specified that the direct assessment of operating costs for a supersonic vehicle is rather difficult and uncertainty-affected for different reasons.

Firstly, the lack of supersonic civil transport aircraft powered by liquid hydrogen actually made means that there is no real reference data which to compare with the results obtained with mathematical models.
This will involve the use of data relating to conventional aircraft actually built and bibliographical references of experimental aircraft (representative anyway a rather limited database).
The impact of technologies related to the use of liquid hydrogen will bring with them substantial changes in aircraft design, usage-related procedures and all the infrastructure related to the use of the latter.
All this will lead to an inevitable change in the cost of acquiring the aircraft.
For completeness, some relationships will be clarified that link the acquisition price of the vehicle according to some design parameters (i.e. maximum take-off weight or thrust).
Some preliminary steps will precede the assessment of direct operating costs. The various voices inside a typical life cycle cost of an aircraft will be illustrated. This will focus in particular on direct operating costs, as these are the main subject of this study work.
Some methods for evaluating costs will be briefly described, then going to illustrate the operating cost values for our reference aircraft. On the basis of these, the main differences on the obtained estimation values will be analyzed.

An overview of supersonic aircraft will also be presented. Describing the evolution of the supersonic vehicle from the forerunners who made history to vehicles which will be product in the future.
The most important means of reference will therefore be exposed before arriving at our reference aircraft (some of these aircraft are just prototypes or simple studies).
The reference aircraft used for cost estimation, the Green Concorde [7], will be described, showing its main characteristics, giving particular emphasis to the: design, fuel system and typical mission profile.
Next, a deep explanation of NASA's reports [2] from a technological point of view will be presented. For the equations of direct operating cost of fuel and maintenance, it has been defined which are the technological drivers, which have the greatest impact on these cost elements.
In the case of fuel, the importance of the market price of fuel is analyzed, especially because in the case of liquid hydrogen it can have reasonable differences with the different production and supply scenarios.
In the case of the maintenance equation, the link between each equation term and the possible level of technological development is analyzed.
Equations are also analyzed according to different mission profiles. Thus, giving the opportunity to evaluate the impact of the propulsion strategy on the total DOC.
Next, the Excel file developed for cost evaluation is described. It uses NASA method equations to evaluate direct operating costs [2].
Finally, the results of the direct evaluation of operating costs for Green Concorde [7] are presented.
The results obtained with the various methods are compared, and there is also a further comparison with the direct operating costs of the Concorde and an equivalent subsonic aircraft in order to understand how economically feasible this technology can be.

2. Introduction to cost analysis

The Cost analysis for a project is of fundamental importance within the industrial sphere.
The economic feasibility of a project must be determined from the earliest stages of the project, in order to understand whether the solution is actually feasible with the resources available to the manufacturer and to understand, whether it will be possible to achieve success on the market from an economic point of view.
Inside this chapter, they will be described what are the typical cost items in the aerospace field and some methods to be able to estimate them.
In the first place, the phases of the life of an aerospace product will therefore be described.
For each of them, some of the main cost items will be illustrated, thus composing the so-called Life Cycle Cost (LCC) containing all the cost headings in an aerospace product (start from the early stages of design until its disposal).
In particular, will be focused on the direct operating costs (DOC), which represent the majority cost item within an aeronautical program.
For each phase, therefore, some of the mathematical methodologies present in the literature will be reported for the evaluation the costs inherent in each of these.

2.1. Airplane Program and Life Cycle

The evolution of the life of an aerospace product is characterized by some typical phases.
According to Roskam [3], the Airplane life cycle is characterized by six phases. The first three phases are related to the design of the product (conceptual design, preliminary design and detail). The fourth phase is related to production of the aircraft, followed by the operative phase of the product and from the disposal of the latter.

Figure 1 - Representations of the life cycle of an aeronautical product [37]

The total cost of an airplane program incurred during the life cycle of an aircraft is known as the Life Cycle Cost (LCC).

Generally, with the aim of estimating costs, it is usual to divide the aeronautical program into four typical phases:

- Reserch, development, test and evaluation cost (RDTE)
- Acquisition cost
- Operating cost
- Disposal cost

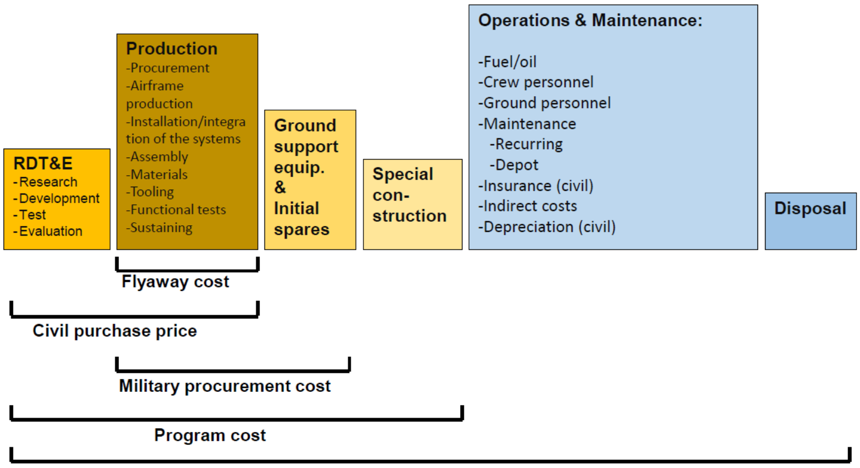


Figure 2 - Breakdown of the various phases of the Life cycle cost [6]

As shown in Figure 2, for each of these phases it is possible to associate a certain category of cost items.
The costs within the RTDE phase are related to the study of new technologies and product development, in addition there are present also cost items related to tests and validations.
With regard to the production phase, the cost items relative to this phase are primarily related to all those terms that physically compose the product such as materials and assembly, in addition we find the manual labor used for the realization of the product, the cost for the realization of assembly lines, buildings and machinery for production (in some cases especially in the space field being the aircraft of the unique pieces are required of unique production machines). In this phase we also find cost items related to the realization of spare parts (when an aircraft is produced all spare parts are produced for give it support throughout its operative life) and functional test to be conducted on complete aircrafts before put them on the market.
During the operational phase, the costs present refer to all those elements that an aircraft will have to face during its use by the customer. These items can be grouped into two categories: direct operating costs (fuel, cabin crew, ground staff, recurrent or extraordinary maintenance, insurance and depreciation) and indirect operating costs (depreciation, overhead, taxes).
During the last phase of the life of the aeronautical product there are the disposal cost of the vehicle. It should be stressed that, in the civil field, in some cases this item can represent a gain and not a cost. This result is obtained from the sale of components that can still be used, or even from the gains deriving from the simple sale of recyclable materials of which the vehicle is composed.

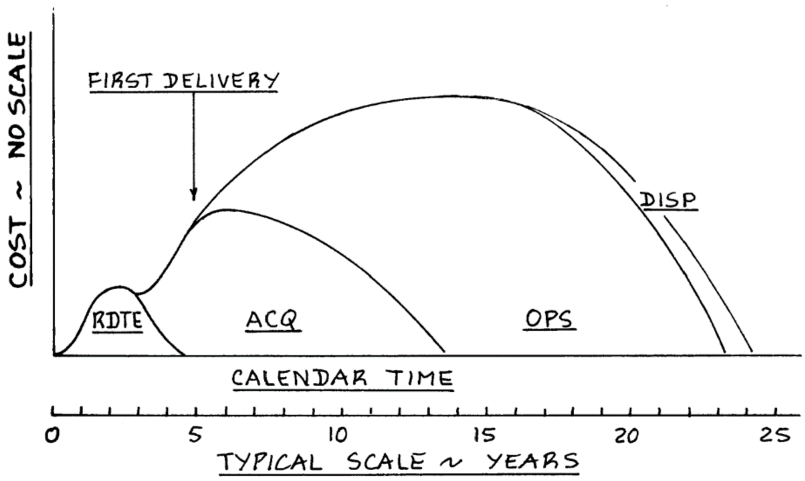


Figure 3 - Representation of the costs of phases throughout the life of an aeronautical product [3]

From graph show in the figure 3, it can be seen that there is a certain overlap between the various stages of life of an aerospace product (e.g. the start of the production phase can also anticipate the conclusion of the design phase). Furthermore, it can be observed that the higher cost items refer to operating costs, which not only reach the highest cost values, but generally persist in more during the life of the aircraft (the area underlying this curve is much greater than the sum of the remaining phases).

A further subdivision that can be adopted, is based on considering separately the items relating to the costs necessary for the acquisition of the aircraft from the costs necessary to keep the latter operative.

In this case, if we want to consider the stages of life previously described, the first category brings together the first two phases of the aeronautical program. Therefore, starting from the design up to the realization of the vehicle, all the costs that will define what will then be the basic price of acquisition of the aircraft on the market can be evaluated.

On the other hand, as regards the second category of costs, these, as already mentioned above, represent the useful costs necessary to keep the aircraft operative and to disposal.

Nevertheless, to clarify the concept of the importance of operating costs, Professor Jan Roskam [3] presents an example of what is commonly known as “the iceberg effect”.

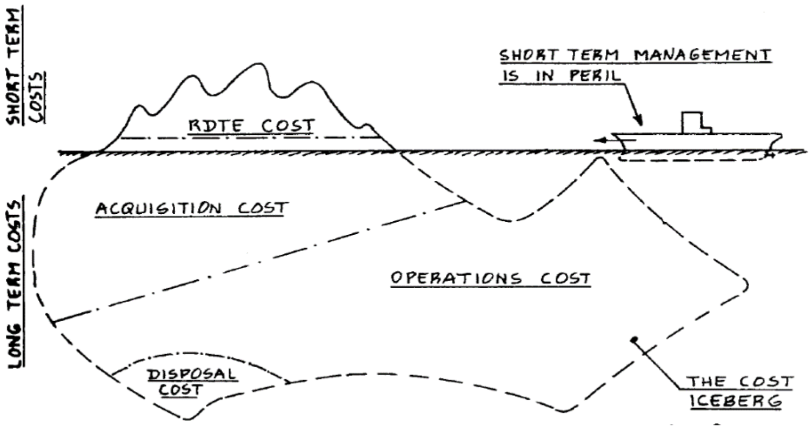
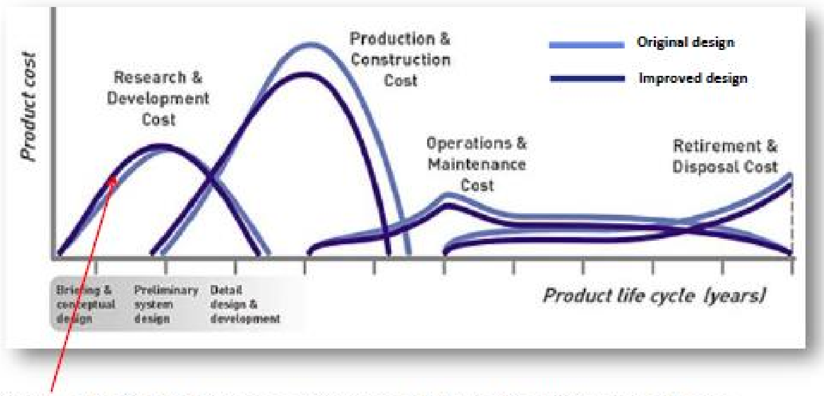


Figure 4 - The Iceberg effect proposed by Jan Roskam [3]

As can be seen in Figure 4, in the early stages of the project it is possible to see (at the cost level) only the tip of an iceberg representing short-term costs. In fact, the most part of the costs is hidden behind the line of sight, under the water surface, where there are hidden the production costs and the operative costs, both of which are considered to be long-term costs. The latter represent the largest part of the iceberg.
The importance of this concept, combined with the lack of foresight, in the past has led to the bankruptcy some companies die which have not considered (or have not been able to assess correctly) the trend of operating costs.
In addition, it should be specified that, trying to reduce the short-term costs associated with the research and development phases could have a harmful effect, unfavorably affecting production costs and even more so on the operating costs that will be incur by the airline during the use of the aircraft.
This consequence, is based on the concept that all decisions made during the preliminary design phases have a significant impact on the cost trends of the entire life cycle of the aircraft.



Often, a studied small increase in investment during the R&D phase allows a notable reduction in LCC costs.

Figure 5 – Impact of reduction of investment in RTDE phase on the other aeronautical life program phases [6]

Currently, the ever-increasing level of competitiveness characterizing the aviation market forces designers to anticipate cost estimates at the beginning of the design process (whit the aims to maximize the profits of all the protagonists company).
In fact, the objective of the aerospace industries is to maximize its profits deriving from the difference between the selling price and the cost of design and production.
On the other hand, for air companies, for maximizing their profits, they need to buy the airplane at low price and to have a limited expense to keep it operative.
The profit in this case is related to the sale of services to customers.
During the design phases, to decree the success of a vehicle on the market, it is necessary for designers to work for create a vehicle that is economically feasible. The realization of aircraft with a low production cost and above all with low operative costs, can induce their purchase by possible customers (always in relation to a trade-off with performance to maximize cost-effectiveness), thus trying to maximize over time their profits and therefore their commercial success.
It should be noted that, the value of costs and profits are linked to inflation in the relevant fiscal year, and because aerospace projects generally last several decades, this it makes it difficult to estimate these elements. That is why it is very important that we are able to correctly estimate the aircraft's life costs in the early stages of design.

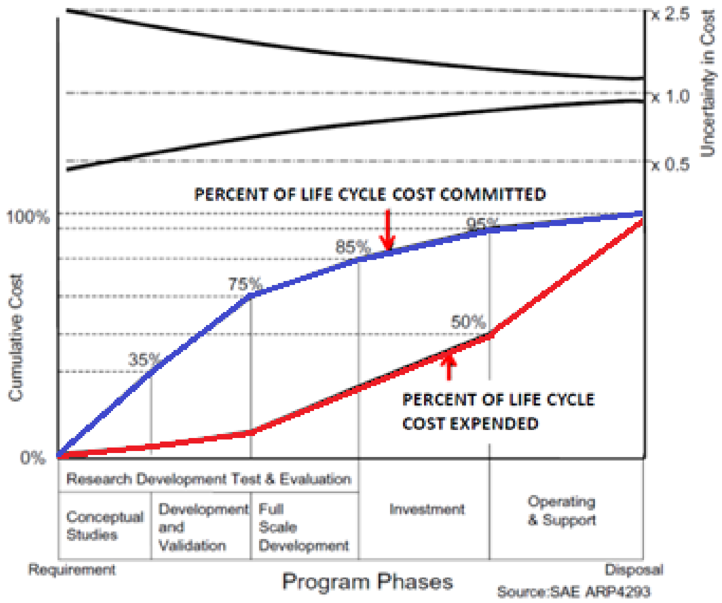


Figure 6 – Comparison of Virtual and real cost during life cycle [14]

In Figure 6, the life phases of an aerospace product and the total cost (expressed as a percentage) are reported respectively within the axes, we can observe several curves that explain the importance of proper design during the early stages of the project. The curves present in the diagram, go to represent the costs really supported and those virtual or estimated. The trend of these two curves is profoundly different, however over time both curves come to convergence.

As can be seen from the curve of costs actually incurred (red curve), during the first phase of design, the cost will remain low (in some cases even below 1% of total costs). This is due to the lower cost of personnel (mainly researchers and engineers) and facilities. Subsequently the curve will undergo a slight increase during the detail design phase. This increase is simply due to an increase in staff employed for the design.
The design phase will be followed by the production phase in which there is a clear increase in the real cost curve. Here, the cost actually incurred increases considerably because it increases the cost related to the staff employed, the raw materials used and the buildings in which the production is carried out.
During the same life phases, in comparison with real cost, the curve of the virtual costs (blue curve) has a remarkable different course. In fact, this curve, already at the end of the conceptual design can represent even 60% of the estimated costs and reach 80% at the end of the detailed engineering.
This high variability is due to the possible reconfigurability of the architecture of the vehicle and of the various subsystems, and to the fact that during these phases' decisions are taken that will have a fundamental impact along the entire life of the product. In principle, moreover, the production costs and the costs of the subsequent phases will already be defined. In fact, after the design phase the virtual cost curve tends to flatten quickly.
Finally, on the same graph there are two curves (black curves) represent the uncertainty of costs related to the ease with which during the various phases, modifications to the project can be undertaken.
As already explained, for the virtual cost curve, it will be during the initial design phases that the aircraft and subsystem architecture may vary. This possibility will then be reduced over the life cycle. Indeed, going to make changes after the design phases could be very high in terms of cost.
All this makes understand the importance in knowing the costs already during the first phases of design.
The knowledge of the costs allows the design company to realize a project that gives at the producer and the customer the opportunity to make the most profit possible.
In this regard, a modern design approach, known as "Design to Cost", is based on being able to change the cost of a product starting from its design.

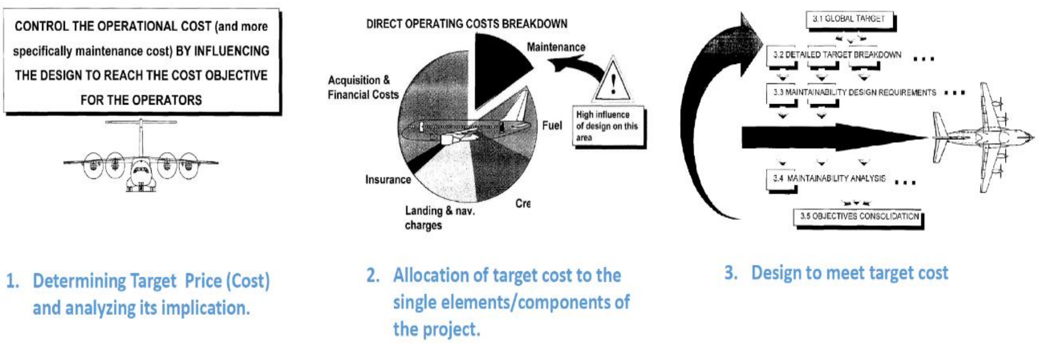


Figure 7 - Some detail of "Design to Cost" approached [6]

The cost in this design approach is no longer seen as a consequence but as a requirement, so the product development takes place by pursuing this requirement and going to overturn what is the perspective compared to a classic design approach, analyzing the different construction solutions, to understand which is the one with the lowest cost and only then evaluate its performance.
This approach therefore starts precisely with the intent to subdivide and allocate the various cost items going then to negotiate with the other requirements, resulting therefore a balanced activity between costs and performance.
Starting from the design to cost, it is possible to negotiate the performance requirements with the customer with the aim of obtaining a certain cost.
This type of approach is based primarily on a sensitive analysis to understand what parameters can act, avoiding the risk of an ineffective negotiation with the client (in the event of lack of knowledge of the correct parameters).

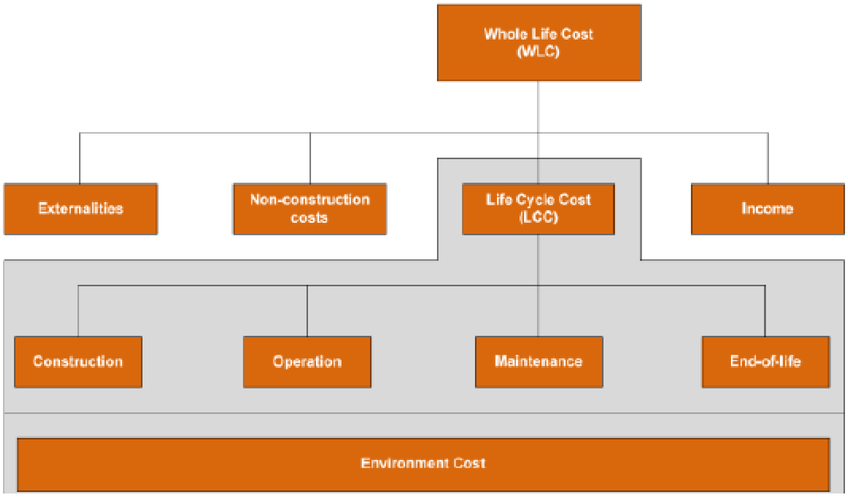


Figure 8 – Cost breakdown structure from ISO 15686-5 [18]

Finally, it is very important to mention a new cost estimation process called Whole life cycle cost WLCC.
The whole life costs calculation adds to this the non-construction costs (e.g. land), income from the asset (not revenue) and externalities such as CO_2 emissions.
The life cycle cost (LCC) is a part of the whole life costing (WLC)
It is very important for this type of estimate goes to carry out a more in-depth analysis than the simple phase of operation of the vehicle once in the hands of the customer. In fact, in this case, all externalities will be evaluated, that is to say, all those cost items that are not immediately visible but that will still have an impact on the customer. They occur when somebody who is not directly involved in a transaction (generally society) incurs a cost or enjoys a benefit as a result of that transaction. For example, cost of the CO_2 emissions.

2.1.1. RDTE cost

As above describe, the costs relating to the first three phases of the life of an aerospace project are grouped under the category RDTE.
This category involves all those activities that develop from the conceptual design and planning stage to the certification of a new product.
Part of these activities consist in the design, construction of prototypes to use for tests on the ground and in flight flying that static.
RTDE cost are normally broken down into seven cost categories:

- Airframe Engineering and Design Costs - C_{aed}
- Development Support and Testing Cost - C_{dst}
- Flight Test Airplanes Cost - C_{fta}
- Flight Test Operations Cost - C_{fto}
- Test and Simulation Facilities Cost - C_{tsf}
- RDTE Profit - C_{pro}
- Cost to finance the RDTE phases - C_{fin}

The total RTDE cost for a new airplane program may be estimated from:

$$C_{RTDE} = C_{aed} + C_{dst} + C_{fta} + C_{fto} + C_{tsf} + C_{pro} + C_{fin}$$

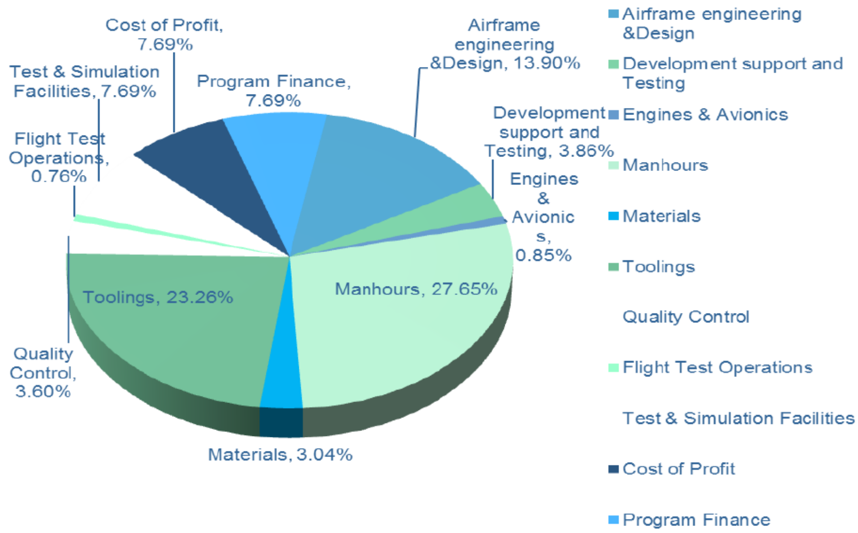


Figure 9 - Typical NRC Breakdown for Boeing 737-800 A/C (from Dev. of LCC for Conventionaland UnconventionalAircraft, Delft Universityof Technology) [6]

Normally the method for estimating RDTE cost can be applied to military as well as to commercial airplane programs. However not all airplane programs are aimed at eventual production. Some are started only for reasons of developing or demonstrating some aspect of advances technology.
It should be noted that, in recent years the advent of new software to support design (e.g. software for computer aided-design, modeling and simulation) have greatly helped design companies by reducing in part the costs related to design and testing.

2.1.2. Acquisition cost

The costs characterise the fourth life phase of an aeronautical programme are related to realisation and acquisition of the project.
It is important to define first the number of aircrafts to be built during the program N_{PROG} (seen as the sum of the aircrafts produced during the RDTE phase plus those produced during the actual production). These are necessary for distinguish manufacturing costs from acquisition costs.

$$N_{prog} = N_{RDTE} + N_m$$

The acquisition costs are expressed as sum of the manufacturing costs plus the term linked to the profits that the producer wants to derive from the sale of the aircraft.

$$C_{ACQ} = C_{MAN} + C_{PRO}$$

It is plausible that, a company operating in the aeronautical sector works with the intention of making profits from its business. These profits are derived from the cost of the plane. Generally, in order to make such profits, you adopt a profit factor (F_{PRO}) of 0.1, this factor is multiplied by manufacturing costs to be able to understand what will be the profit that the company will have from the sale of the aircraft. However, this factor is not univocally definite but may vary significantly depending on market conditions and particular business policies.

$$C_{PRO} = (F_{PRO})(C_{MAN})$$

The price paid by the user of an airplane (which is his acquisition cost) depends on a number of factors:

1. the total number of airplanes built by the manufactures;
2. The number of airplanes acquired (generally, in commercial programs there isn't only one customer. Every customer buys only a little percentage of total built. In military sector instead the number of airplanes acquired is often the same of the number of built airplanes;
3. The manufactures profit which can be negotiated: for large fleet buys a manufacture often offers a lower profit to enhance his market share;
4. The cost of the RDTE program C_{RTDE}.

An estimate of the unit price per airplanes can be obtained from:

$$AEP = \frac{(C_{MAN} + C_{PRO} + C_{RTDE})}{N_m}$$

This assumes that the RDTE are not sold during the program.
Another assumption is that no spare parts are bought by the user. In most cases commercial and military customers will want to buy a certain number of spare parts, very important for maintained the vehicle during the operative phase.

The total airplane program manufacturing cost can be broken down into the following cost categories:

- Airframe Engineering and Design Cost - C_{aed}
- Airplane Production Cost – C_{apc}
- Production Flight Test Operations Cost – C_{ftom}
- Cost of Financing the manufacturing program – C_{fin}

$$C_{MAN} = C_{aed} + C_{apc} + C_{ftom} + C_{fin}$$

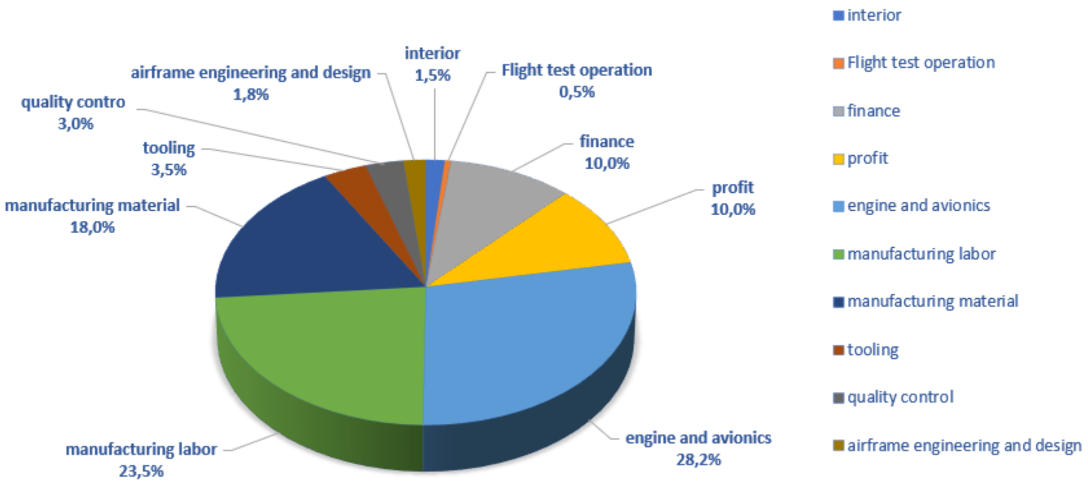


Figure 10 - Typical Breakdown of purchase cost of Boeing 737-800 A/C [6]

Through the chart shown in the figure 10 it is possible to observe the decomposition of the purchase cost. Here a large portion is occupied by the cost of the engine and avionics (about 30%). In general, these systems are purchased from external suppliers.
Historically, avionics is the system that has had the highest price increase.
Nowadays, the costs of avionics are the highest compared to any other subsystem (especially in the military sector where they can exceed 40% of the cost of production). In the civil sector, in fact, avionics costs can vary between 5 and 15%

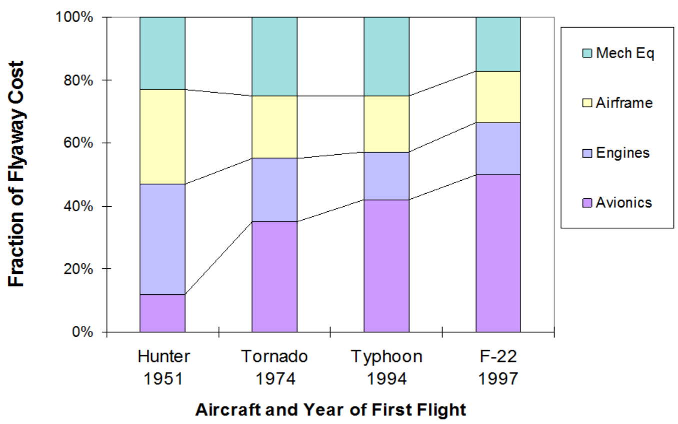


Figure 11 - Subsystems cost evolution for military aircraft [6]

Another major item within this scheme is related to the cost of manufacturing hours. This cost is still quite high because the production cycle of aerospace products is still not very automated and very manual, and in some cases requires solid foundations and qualified personnel.

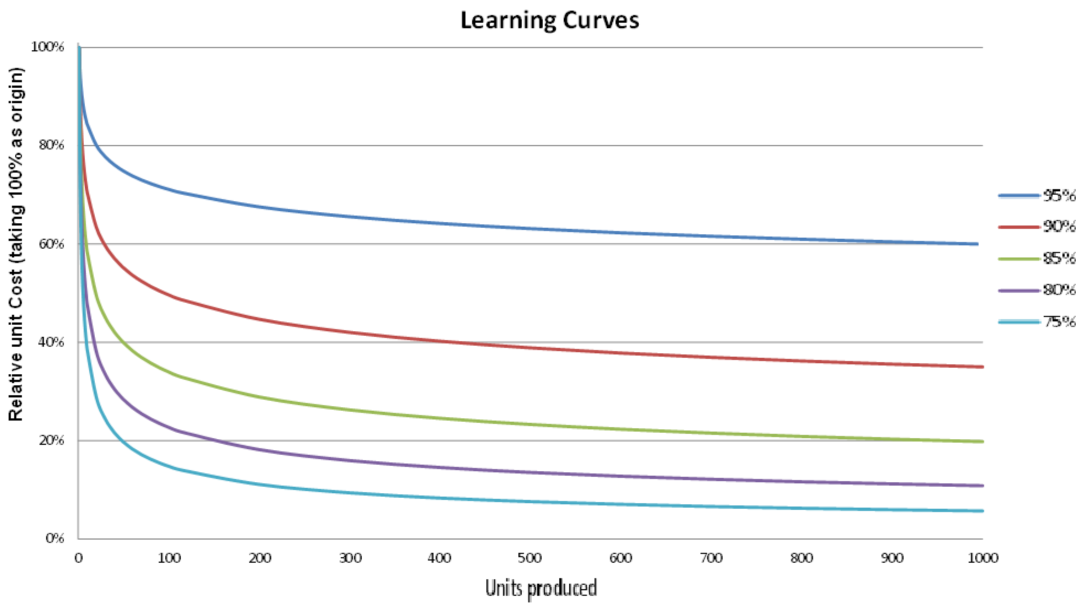


Figure 12 -Boeing 787l Learning curve diagram (cost units vs produced units) [19]

However, it is important to undermarked those manual processes are characterised by the so-called learning curve. The experience gained by workers as the number of aircrafts produced increases means that the time required for the production of the individual aircraft decreases, thus also reducing the cost of manufacturing hours.
The graph in figure 12 shows different curves that refer to different production scenarios.
According to the reference [60], production costs per vehicle are reduced by about 20% when the quantity of production is doubled. However, when production reaches high production values, the curve tends to settle on a constant value. Typical values of this curve in aerospace range from 73 to 80 %.
A similar effect can also be observed for RTDE phases (hyperbolic degrowth is observed).
According to the reference [3], the learning curve effect can be expressed through the formula:

$$MHRS_{unit} = \frac{MHRS_1}{N_{prog}^n}$$

- $MHRSunit$ is the required manhours per unit
- $MHRS1$ is the manhours required to build the firs unit
- $N\_program$ is the number of airplanes built
- n is the learning curve exponent, depends on percentage of learning curve.

For P percent of learning curve, the exponent n may be found from $P=100/2^n$
This effect shows (especially in the manual job) as an increase in the units produced leading to a reduced production time per unit and consequently of the production cost.
The relative part to the costs of the materials legacies to the structure is of approximately 18%.
Other cost items still include part of the engineering. This is related to specific requests from the customer that deviate from the initial requests and in addition, there are studies that aim to improve the production cycle.
We can observe 10% of the financial part in the items of profit (This item is due to the interest on bank loans obtained by the producer company in order to start production).
According to reference [3], finally, there are some parameters that play a key role in determining the cost of production thus determining the price of the aircraft:

- Airplane take-off weight - this is relevant when the number of aircraft produced is low.
- Airplane design cruise speed – an increase of this parameter brings the cost of the aircraft to rise considerably, especially when the units produced are in limited number.
- Airplane production rate
- Airplane RDTE cost and number of airplanes over which cost is to be derived.

2.1.3. Total Operative cost

As already explained, the majority cost items within life cycle cost are to be attributed to operative costs. By the term operating costs or total operating costs, we indicate the sum of direct operating costs (DOC) and indirect operating costs (IOC).
The estimation of operating costs is very complex as it is subject to several variable, one of this is the time dependence. This dependence on the time factor creates a considerable level of complexity especially if we consider that on average an aeronautic program can last some decades.
In addition to time-dependent variables, there are also variables related to economic factors (cost of fuel, personal salary maintenance).
These costs will accompany the aircraft throughout its operational life.
If one wanted to estimate the total operating cost of a given aircraft it would be necessary to sum the sum of all direct operating costs generated by that particular aircraft used by the i-th customer for the number of aeroplanes purchased by the customers with the sum of all indirect operating costs generated by that particular aircraft used by the i-th customer also in this case for the number of aircraft purchased by the i-th customer.

$$C_{OPS} = \sum_{i=1}^{n} (C_{OPS_{dir}})_i \, (N_{Acq})_i + \sum_{i=1}^{n} (C_{OPS_{ind}})_i \, (N_{Acq})_i$$

In recent decades, the trend on the part of airlines has been to reduce as much as possible the cost items within this category in order to be able to maximize their profits.

Direct operating costs, unlike indirect costs, are related to the design of the aircraft. As this thesis work focuses on the estimation of direct operating costs, these ones will be analysed in more detail in paragraph 2.3. dedicated to them.
Indirect operating costs are only partly directly related to a specific type of aircraft. Although aircraft design can have a significant influence on indirect costs (e.g. requiring new maintenance facilities and the introduction of new skills for technological advances) it is difficult to quantify this interrelationship.
The management of airlines and operational aspects are predominant factors in indirect costs and these are outside the control of the aircraft designer.
They vary significantly from one operator to another.
Typically, their cost estimation is based on costs per nautical mile and is seen as the sum of several factors.
Taking in reference [4] we can generally observe indirect operating cost items:

1. Facility purchases costs and facility depreciation
2. Facility leasing costs
3. Facility maintenance costs
4. Ground equipment depreciation
5. Ground equipment miniatous costs
6. Maintenance overheads
7. Headquarters overheads
8. Administration and technical services
9. Advertising, promotion and sales expenditures
10. Public relations of cost expenses
11. Booking, ticket sales and commission
12. Customer services
13. Training

Cost Group	Cost Type	Passenger		
		Cost (millions)	Share of Cost	Cost per Block Hour
Direct	Aircraft Operating Expense	$75,227.5	52%	$4,709
	Subtotal Direct Expenses	**$75,227.5**	**52%**	**$4,709**
Indirect	Advertising and Promotion Expenses	$1,218.0	1%	$76
	Aircraft Servicing Expenses	$7,575.3	5%	$474
	Amortization (non-flight equipment)	$604.8	0%	$38
	Depreciation Expense - Maintenance Equipment	$68.8	0%	$4
	General and Administrative Expense	$9,133.0	6%	$572
	Maintenance and Depreciation (ground equipment)	$1,763.6	1%	$110
	Passenger Service Expenses	$9,843.8	7%	$616
	Reservations and Sales Expenses	$6,652.1	5%	$416
	Traffic Servicing Expenses	$12,311.6	8%	$771
	Subtotal Service, Sales, and General Operating Expenses	**$49,171.0**	**34%**	**$3,078**
	Transport Related Expenses	$20,963.5	14%	$1,312
	Subtotal Indirect Expenses	**$70,134.6**	**48%**	**$4,390**
Total Operating Expenses		**$145,362.1**	**100%**	**$9,099**

Source: 2013 Form 41, Schedules P-7 and T-100

Figure 13 - Comparison of the origin of direct and indirect operating cost [36]

Indirect operating costs vary considerably depending on the type of operation and activity of the airline. Standard methods for estimating these costs are available (e.g. "Boeing Operating Cost Ground Rules") moreover, data on actual costs incurred by

airlines are published (e.g. the USA CAB annually publishes statistics and data in journals such as the Flight International and Aviation Week annual reviews).
In order to identify the value of indirect operating costs it is important to know the airline's policy on aircraft and traffic services, promotion, sales and services offered to passengers. A collection of general and administrative costs is also useful, on ground equipment, on maintenance and on structures with their respective depreciation.
In some cases [3] IOC can be estimated as a simple percentage of DOC. Indirect operating costs are between 15 % and 50 % of the total operating costs according to the reference [6].

2.1.4. Disposal cost

There comes a point in time when any airplane no longer has commercial value needs to be disposed. That point is normally reached when:

- The airplane has reached the end of its safe structural life and structural repairs are judged to be not economical.
- The airplane has reached the end of its economic life: it can no longer compete effectively in the face of more modern airplane.
- It has been damaged beyond repair (such as in certain crashes or by damage caused by weather).

The cost of disposing of the aircraft depends on the materials used in the construction and the complexity and danger of the removal and decommissioning operations.
In according to [3], disposal usually consists of:

- Temporary storage
- Draining of liquids and disposal thereof
- Disassembly of engines and other systems (such as computers and instruments)
- Cutting up of the airframe and disposal of the resulting materials

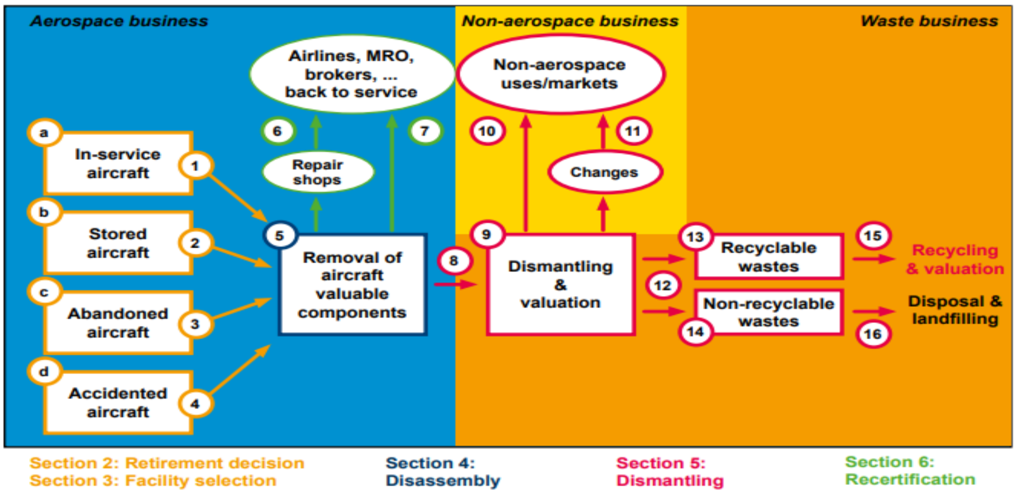


Figure 14 - Flowchart of disused, sold or recycled aerospace components [17]

Each of these items has a cost associated with it, but for some of them, we can see gains that can be associated with the possible resale of components that can still be used or with the sale of simple recyclable scrap and other materials. Any disposal costs are therefore partially offset by these resale values.
In the airplane, materials and liquid are used which pose a problem for the environment if they are not disposed of with care (e.g. beryllium alloys, most composites not bio-degradable, many oils and liquids such as hydraulic fluids).
Is a responsibility of designers include in their design decision making process some serious solution about this problems. It is not ethical to ignored this problem.
To estimate the disposal costs with credibility it is necessary to use the help of chemical and environmental engineers in the design decision-making process.
At present, since there is no precise wording for estimating disposal costs, they are usually considered as 1% of the LCC
Whether or not this accounts fairly for the actual balance between resales values and disposal costs is very much an open question.

2.2. Direct Operative Cost

As stated in the previous paragraphs, operating cost items are the largest cost items within a typical life cycle cost, reason why, that is why they will be exposed with greater completeness.
The main bibliographical references refer to some typical cost categories for DOC:

- Standing Charges (depreciation, insurance, interest charges)
- Flight Costs
- Maintenance Costs
- Landing /Navigation Fees

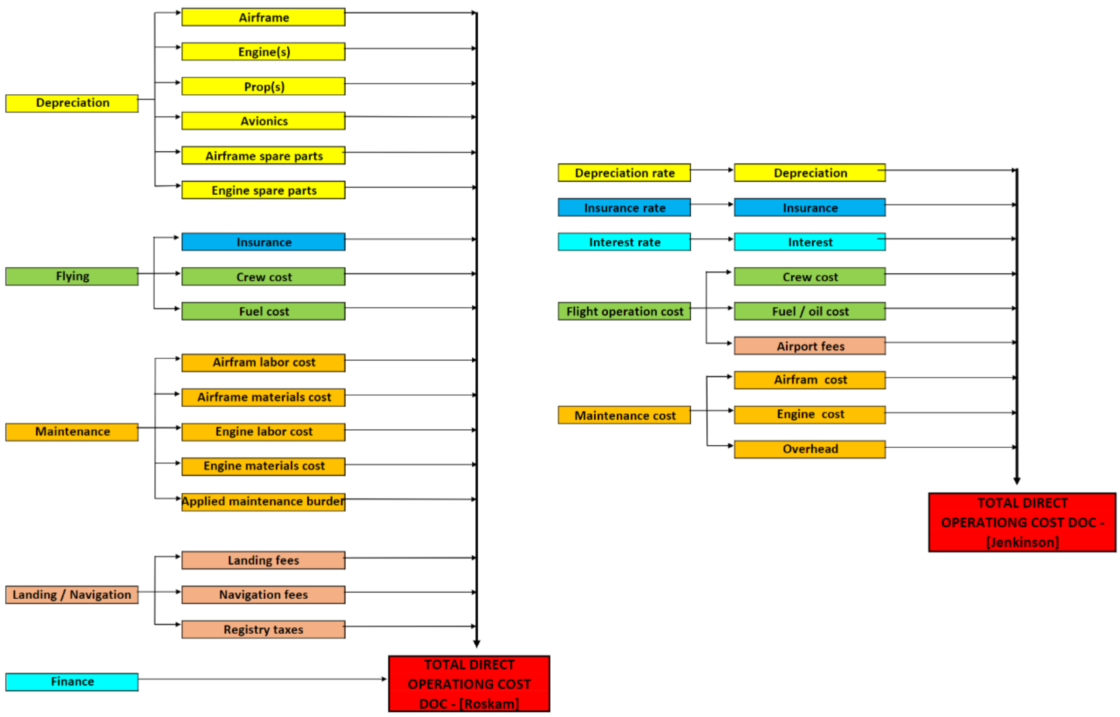


Figure 15 - Comparison between various cost items present within the DOC models proposed by Roskam and Jenkinson

For a civil aircraft, the typical breakdown of direct operating costs and percentages of items is shown in Figure 16.

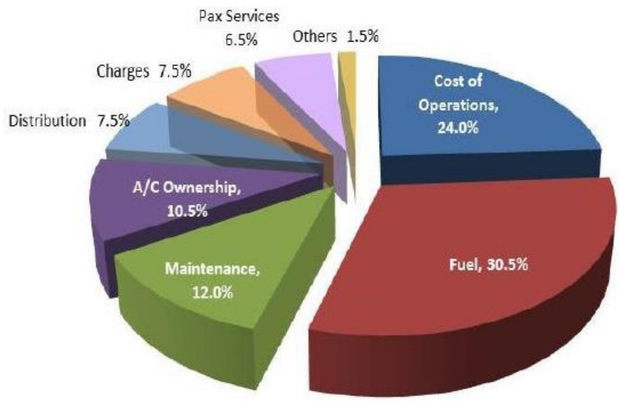


Figure 16 - Typical DOC breakdown [6]

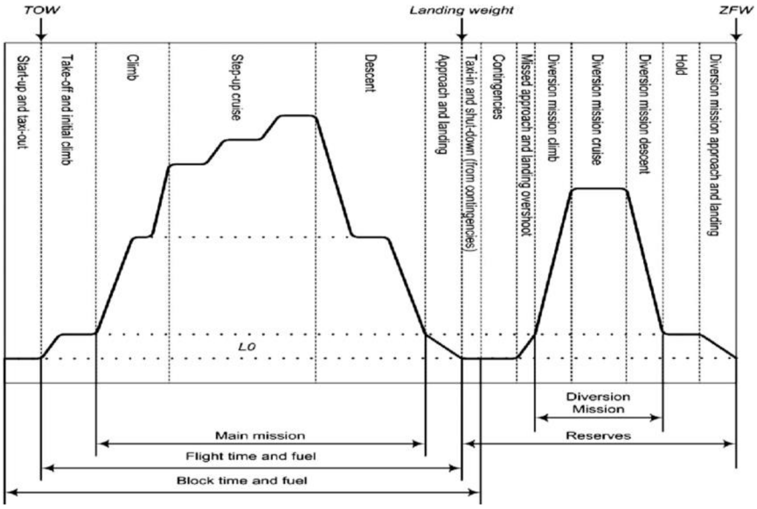


Figure 17 - Typical mission profile for a generic civil transport aircraft [38]

The reference data [3] stress that the main factors having an impact on direct operating costs are:

- Block distance
- Crew salary
- Fuel price
- Specific fuel consumption
- Airframe and system maintenance manhours per block hour
- Take-off weight

We define as block distance the distance travelled from the aircraft, considering also the phases that anticipate the take-off and that accompany the means until after the landing.
An increase in block distance leads to a reduction in direct operating costs, as they tend to reduce several components such as fuel cost.
It is interesting to see how fuel is the most important cost item. The price of fuel has a strong effect on the DOC. If the price of the latter increases, the DOC will have the same tendency to increase.
In addition to the cost of fuel, another important item is related to the cost of maintenance required to keep the aircraft operational. Indeed, where a major effort is required for maintenance, this will result in an increase in direct operating costs.
Crew salary have a weak effect on direct operating costs.

As already mentioned, for civil aviation, operating cost items can easily reach 80% of the total life-cycle cost [3].

2.2.1. Standing Charges

Analyzing the first category, or the one related to standing charges, we can see that these items are not "directly" connected to an aircraft flight, but are considered as "overhead" on the flight. This category consists of:
1. aircraft insurance;
2. interest charges on capital employed;
3. depreciation of the capital investment;

Interest charges e depreciation is often placed under a single item called "cost of ownership".

As regards the cost of insurance:
this cover [3]:
- the risk of in-flight and ground damage to the cell or its possible total loss;
- the liability of passengers for possible accidents or death;
- the liability for third parties in the event of death or injury;
- the risk of damage to cargo;

The airline can choose whether to take out an insurance policy that covers all the damage to the facility or only part of it.
As is well known, airworthiness authorities monitor compliance with safety standards by establishing and consolidating the risk value of an aircraft accident (for ICAO civil transport aircraft it has set the value of 10^{-9} hours of flight time per catastrophic accident [37]).
Based on the values provided by the authorities, insurance companies can easily estimate the technical risk associated. This is directly linked to the failure rate of the vehicle and therefore to the probability of occurrence of an accident.
In addition to this basic technical risk, there is the possibility of losing your vehicle due to non-technical events (e.g. sabotage or human error). Such risks are difficult to determine beforehand because of the sometimes-random nature of the problem.
Generally, in civil aviation, according to [53] the causes of losses of the aircraft are estimated for:

- 54% pilot mistake
- 24% mechanic failure
- 9% sabotage
- 8% weather

Insurance companies therefore tend to vary their fees according to the nature (e.g. geographical areas of flights) and the levels of safety offered by airlines during their missions. It is possible to observe a relationship between the cost of an insurance policy and the rate of loss of the aircraft or "Actuarial losses", in fact, as the rate of accidents of a aircraft increases the cost of insurance.

According to [6], typical values of annual premium for securing an aircraft vary between 1% and 3% of the cost of the aircraft. At this point, if you want to estimate the value of the cost related to insurance, you can use as typical values [6] 1,5% of the cost of the aircraft or [3] 2% of the DOC.

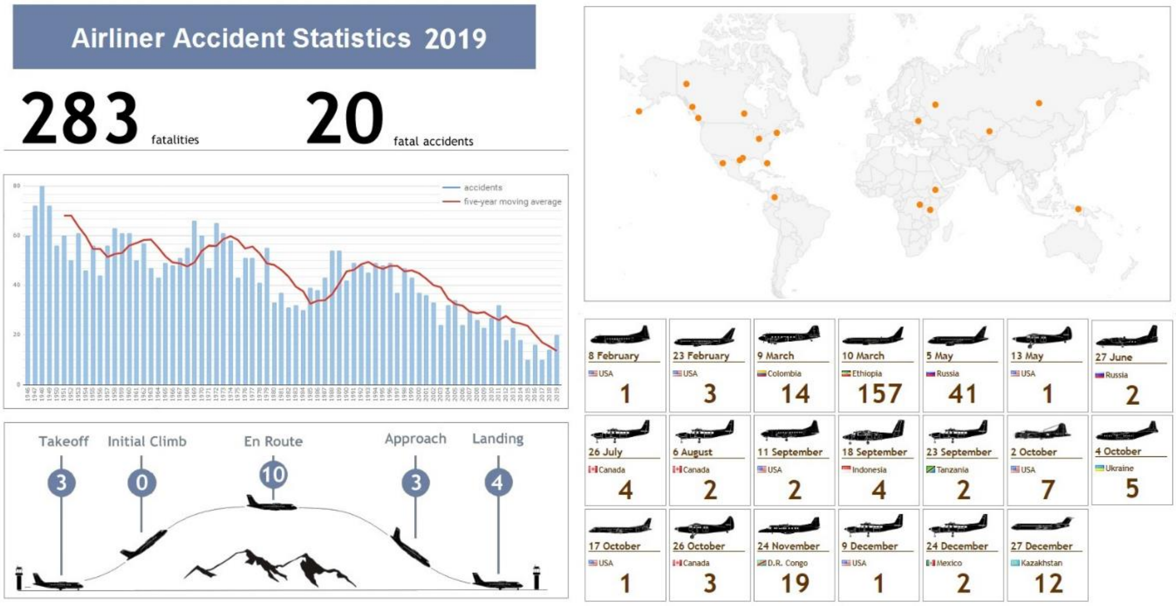


Figure 18 - Decreasing trend in years of aviation accidents [20]

As regard the Interest charges:
These appear to be almost impossible to quantify in a general cost analysis as they depend on the banks and government agencies that will charge the various fee items to the air companies. These charges depend on the global economic climate, local exchange rates, the buyer's credit position and the encouragement given by the national government to the airline or producer. Moreover, further complications of the estimation may arise due to agreements between trading partners (e.g. between manufacturer and airline).
Given the external influence on these factors, many cost estimation methods ignore this cost component, however, you need to include them in any business plan.
A method for estimating finance and interest costs according to [3] refers to the simple "rule-of-thumb". Based on observations of typical financial costs, this rule gives this cost item 7% of DOC.

AS regard depreciation cost:
We can consider depreciation as the most important item of the standing charges. As explained in the ref. [3] it is possible to associate a depreciation plan not only to the entire aircraft but also to subdivide it for the different subsystems of which the aircraft is constituted (airframe, Engines, propellers, avionics, spare parts).
It is linked to a number of factors including: capital invested, airlines' purchasing policies, accounting practices of loan and finance companies, competition for global capital and global economic conditions at the time of purchase of the aircraft.
During its operational life, as required by regulations, the aircraft will always be maintained in airworthiness condition. A residual economic value can therefore be

associated with them over the years. In this case the residual value will tend to shrink as the aircraft ages.
At this point, we can define the depreciation period as the period necessary for the aircraft to lose all its residual value.
This will depend on the airline's accounting policy and the planned development of the routes for which the aircraft is purchased and put into service.
Typical values of the useful life of an aircraft range from 15 to 30 years, where at the end of these it is possible to consider as zero its residual value. It should be mentioned that, in accordance with sustainable design, the current trend for civil aircraft is to progressively increase the useful life of the latter by going to carry out operations to upgrade the platforms.
The choice of depreciation period and the estimate of residual value are calculated by the airline during the purchase phase (e.g. 12 years depreciation at 15% residual value). From this, it is clear that the main parameter in the valuation of the depreciation schedule is the total price of the aircraft.
The initial price of the aircraft used in the depreciation assessment will include an allowance for the capital needed to also provide spare parts (typically 10-15% of the initial price of the aircraft) to assist the aircraft throughout its operative life.
It should be noted, however, that the estimation of the price of the aircraft is complicated, especially during the initial phases of the design, since it depends on many factors, not only Engineering but also economic in nature.
In reality, the price of the aircraft will not be constant but will vary during its production. Its average price will be discounted both at the beginning and at the end of production to be able to satisfy the market. From here, it is possible to understand how the only rule that seems to apply to the price of aircraft is aimed at satisfying the market and not as a complex calculation of design and production cost, although the latter aspects cannot be overlooked at all since all the actors involved need to profit from them (the producer from the sales to remain in business and the airline must profit from the purchase at an advantageous cost).
With the complexity and uncertainty of the factors associated with the market price for aircraft however interesting to observe in some cases a good relationship between the cost of the vehicle and its operating weight. With this report it is possible to observe in the first instance that the price of the aircraft is directly proportional to the weight of the latter. However, this report can only be used for preliminary estimates (using analogy cost estimation methods).
In the case of more detailed estimates, this relationship is no longer accurate and it is necessary to consider high-level methods based on system configurations and details.
A further method to be able to estimate the acquisition price of the aircraft is based on a statistical estimate based on a reference database with within the prices of various aircraft (more data will make the estimate more accurate). In this regard, there are several data sources from which it is possible to obtain information regarding aircraft prices (i.e. the Avmark Aviation Economist database).
Finally, it is important to remember that in the process of creating the database, when using price data, is be necessary perform a proper normalization of values to take into account inflation and currency devaluation.

The percentage of the first cost of the aircraft to be depreciated per year can be determined as:

$$DOC_{depr.} = \frac{\left(\frac{P_{init.} - P_{resid.}}{P_{initial}}\right)}{\left(\frac{T_{depr.}}{100}\right)}$$

Where:
P_{init}: initial price;
P_{resid}: residual price;
T_{depr}: depreciation period.

2.2.2. Flight Costs

Within the second category of DOC costs, we find the cost items associated with the flight itself.
In this case, all bibliographical references agree to insert within this category the cost items related to:
1. Crew cost
2. Fuel and oil cost
In addition to these items, the reference [6] includes an additional item related to:
3. Landing and navigation costs
This item, on the other hand, according to ref [3] should be considered as an appropriate part because there is no agreement on considering this item as a direct or indirect operating cost, instead a cost item to be associated with the flight would be due to the cost of insurance (previously exposed).

As far as the crew cost is concerned, it should be stressed that there may be different approaches for cost estimate. Indeed, often the items related to the salary of flight attendants is considered within the category of indirect operating cost (passenger service expenses). In this case the crew cost assessment is simply related to the fly crew.
In typical situations, the flight crew consists of two pilots (according to airworthiness standards and trade union agreements). This value may grow to three or more depending on the range of the aeroplane and size (the legislation provides rules on the number of hours that can fly per month and the hours of rest and as previously said suggests the presence of a third person in the case of a long mission [61]
As for the number of cabin crew, this is associated with the number of passengers (30-50 passengers per cabin attendant is typical).

Major Airlines Captain Salaries

Airline	Year 1	Year 6	Year 12
Air Canada	$160,000	$268,000	$310,000
Alaska Airlines	$235,000	$245,000	$277,00
American Airlines	$172,000	$277,000	$356,000
Allegiant Air	$166,000	$203,000	$236,000
Cathay Pacific	$133,000	$150,000	$169,000
Delta Air Lines	$271,000	$287,000	$353,000
Emirates	$97,000	$112,000	$139,000
Frontier	$191,000	$218,000	$255,000
Hawaiian Airlines	$218,000	$253,000	$324,000
JetBlue Airways	$239,000	$255,000	$275,000
Southwest	$250,000	$266,000	$285,000
Spirit Airlines	$193,000	$220,000	$257,000
Sun Country Airlines	$121,000	$161,000	$197,000
United Airlines	$270,000	$289,000	$366,000
WestJet	$141,000	$184,000	$131,000

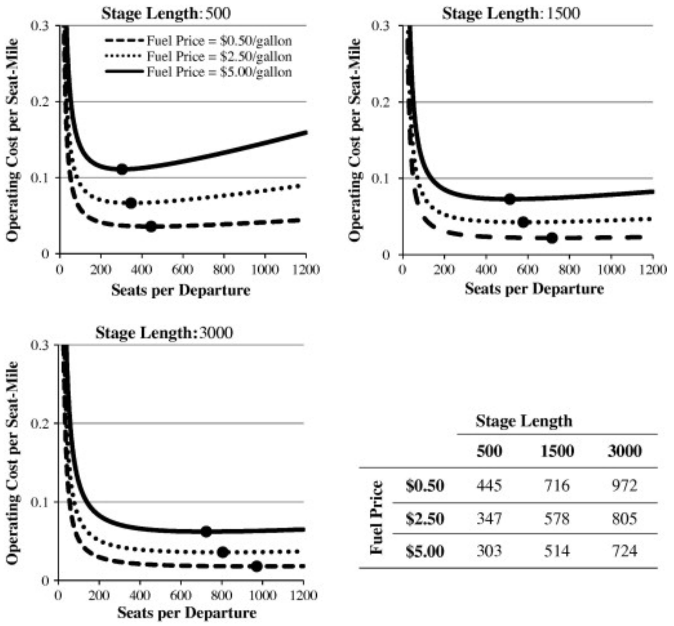
Figure 19 - Airline pilot salary [21]

It should also be noted that flight and cabin crew have different patterns of working hours, the latter generally having more working hours.
The use of the crew is strictly dependent on the contract between the airline and its personnel. (According to [6] a typical value is 800 hours per year for a aircraft-sized regional jet aircraft). Salaries are also very different and vary depending on the airline, the type of aircraft on which to operate (the salary tends to increase with the increase in the weight of the aircraft or its performance), the role invested by the staff and the experience gained over the years by the staff. This makes the assessment of crew costs not very easy.
In addition to the above, there are also extra costs within the cost of the crew due to general expenses for stopovers of long-haul flights (in some cases considered as indirect operating costs) and the cost of training activities and the travel expenses of pilots and benefits granted to them.
Figure 19 shows the average annual salary of the crew for some American airlines. As said before, there may be great differences between one company and another. For estimating these items, the following report can be used:

$$C_{crew} = \left(C_{annual\ fly\ crew\ member} * N_{fly\ crew} + C_{annual\ cabin\ crew\ member} * N_{cabin\ crew} \right) \frac{T_{block\ hours}}{T_{crew\ utilisation\ per\ year}}$$

Where: C is cost, N is numbers of and T is time.

As regards fuel cost, this is the most significant component of operating costs.
It is closely linked to the price of fuel and precisely the volatility in the latter's forecast tends to complicate the estimation of fuel costs over the long term.
Obviously, in this case there is a proportionality relationship between the fuel cost and the operating cost related to the latter.



		Stage Length		
		500	1500	3000
Fuel Price	$0.50	445	716	972
	$2.50	347	578	805
	$5.00	303	514	724

Figure 20 - Capturing the impact of fuel price on jet aircraft operating costs with Leontief technology and econometric models [22]

Some useful strategies in order to reduce as much as possible this item refer to a design that aims to achieve optimal values in terms of aerodynamic efficiency and propulsive efficiency, thus reducing consumption and consequently fuel costs related.
It should be stressed that it is not easy to predict the cost of fuel over the long term, as it depends heavily on the economic variation of the markets.
In Figure 21, you can see the variation in the price of oil and jet fuel over the years. It should be noted that the two curves, although separated by the refining cost have a practically overlapping trend.

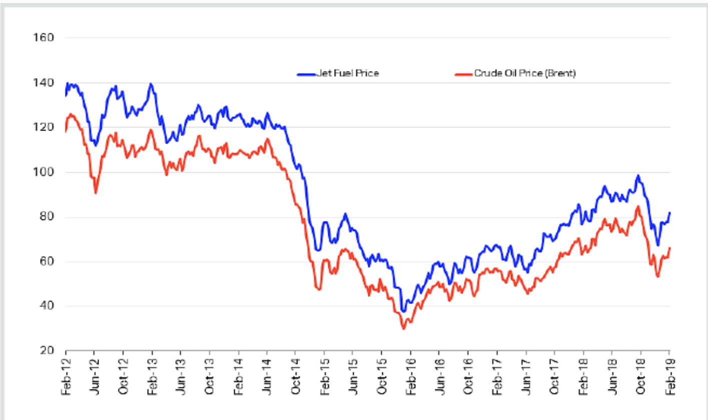


Figure 21 - Jet fuel and crude oil price (USD per barrel) [23]

The last item related to the category of flight costs, are landing and navigation fees. These are described by ref [3] as the sum of three items:
・Navigation fee
・Landing fee
・Registration fee
While navigation fees vary in relation on the route that the vehicle is following and on the states on which the flight is taking place, the other two taxes are strictly dependent on the size of the aircraft, as well as on the airport authorities and the government of the countries in which the vehicles are registered.

2.2.3. Maintenance Costs

The last category of direct operating costs is relating to maintenance costs.
For direct operating costs, maintenance shall be directly linked to the aircraft and its components.
Again, the estimation of maintenance costs may not be an easy job to do as there are numerous items to be included in it.
As can imagine, the maintenance of an aircraft will be linked to appropriate ground maintenance facilities that the air companies will have to have with the related costs of implementation and management (items often included within the IOC). It should be noted that, in some cases the maintenance activity is outsourced (especially for engines) to manufacturers or other companies specialized in maintenance. Therefore, each cost estimation method has a different way of assessing maintenance costs due to a large variability of these relevant cost items.
The being build databases for statistical analysis is very difficult given the lack of availability on maintenance data (for make this task simpler, every year the "aviation week and space technology" publishes maintenance data).
The main estimation models of maintenance costs are based generally on adding up the labor and material costs associated with inspections and maintenance due to the overhaul. All of which is allocated to the airframe, engines, or avionics and the various systems and accessories of which the aircraft is composed.
All standard DOC methods include procedures for estimating maintenance costs, but care should be taken when adapting these standardised methods to particular aircraft designs that require specific tasks for their maintenance.
Most cost estimation methods usually tend to divide CER's to evaluate separately the contribution due to the cell and engines. In general, therefore, it is possible to observe five typical cost items associated with maintenance:
1. Cost of maintenance materials for the airframe and systems
2. Cost of airframe and system maintenance labor
3. Cost of maintenance equipment for engines
4. Cost of labor for engine maintenance
5. Maintenance burden (overhead cost)

Cost allocations between, airframes and systems, engines and maintenance burden are fairly evenly distributed.
Is easy to suppose how an increase of the hours of use of the vehicle corresponds an increase of the hours due to the maintenance.

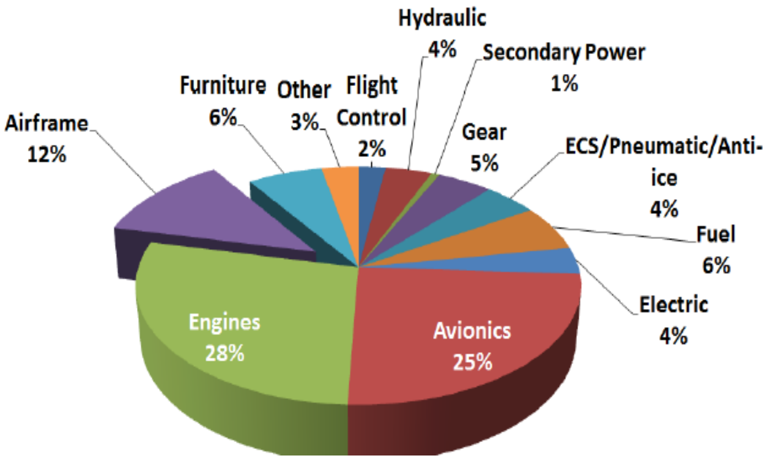


Figure 22 - Breakdown of maintenance cost for the various subsystems [24]

According to the reference [3], some engine and airframe characteristics may have an effect on the maintenance hours. Among these features we find:

- The weight of the airframe; here the hours of service necessary to carry out the maintenance tend to increase with the increase of the weight of the airframe since they are present a greater number of parts to control and eventually to repair, in addition to being in some cases required devices able to handle heavier or bulky components.
- The prices of the airframe; the cost of the cell describes the properties of the material. New materials have higher costs and, in some cases, require more maintenance hours and more accurate maintenance activities.
- The engine thrust; the required maintenance increases with thrust, this because the engines tend to have high-level performance. In this case the prices of the engines being connected to its performance will tend to go up and this will bring with it an increase in maintenance costs (High-level propulsion system requires more accurate maintenance).

Engine maintenance activities are undoubtedly still the most important economic activities to date, but great importance is also given today to the cost related to the maintenance of avionics (that plays an increasingly important role in modern aircraft). Finally, it should be noted that these two elements are also the components with the highest acquisition cost.

2.3. Cost Estimation Relationships

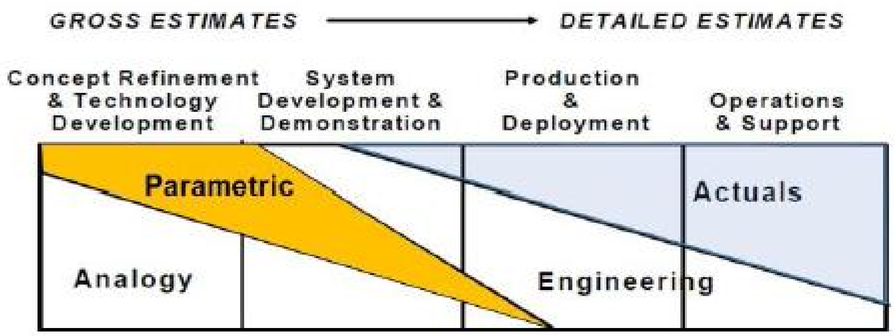


Figure 23 - Different methodologies for cost's evaluation [5]

Depending on the phases of the project, there are different methodologies to make an appropriate estimate of costs. The different methodologies are:

- Analogy: in the initial phase the analogy methodology can be used, this method is used a lot for estimates order of magnitude of cost (generally based on a single driver of the database of reference products). using the cost of aircraft with similar performance or characteristics and through database containing historical references is possible to identify the cost of the aircraft. This method is very simple and fast, but it is only applicable in the early stages of the project, where few data are available.
  Very flexible method, it has as disadvantage the low degree of reliability of the estimate and the subjectivity in the choice of the cost driver.
- Parametric or statistical: is based on the database in which the parameters are reported. Once the database is created, it is very easy to evaluate the costs using different cost drivers, however the difficulty lies in developing such a database. The more extensive the database, the more parameters are taken into account, making estimation more predictive. Moreover, the use of more parameters will make to lose the subjectivity of the choice. This method uses statistical equations based on certain design parameters to estimate aircraft cost.
  The assumption that guides the parametric approach is that the same factors that have influenced costs in the past will continue to influence costs in the future.
- Bottom-Up or Engineering: This is a bottom-up approach in which activities are divided into appropriate categories until get also the most basic task and component (very reliable). The details required for its implementation make it usable only in the last stages of design (much laborious method). Using this method, the design window must know the working principles of each part and the time required for its production.
  Through this methodology you begin to have real costs.
- Actuals: in this category we no longer talk about cost estimation but about costs actually incurred.
- A final methodology could also be to seek expert advice.

Method	Strength	Weakness	Application
Analogy	▪ Requires few data ▪ Based on actual data ▪ Reasonably quick ▪ Good audit trail	▪ Subjective adjustments ▪ Accuracy depends on similarity of items ▪ Difficult to assess effect of design change ▪ Blind to cost drivers	▪ When few data are available ▪ Rough-order-of-magnitude estimate ▪ Cross-check
Engineering build-up	▪ Easily audited ▪ Sensitive to labor rates ▪ Tracks vendor quotes ▪ Time honored	▪ Requires detailed design ▪ Slow and laborious ▪ Cumbersome	▪ Production estimating ▪ Software development ▪ Negotiations
Parametric	▪ Reasonably quick ▪ Encourages discipline ▪ Good audit trail ▪ Objective, little bias ▪ Cost driver visibility ▪ Incorporates real-world effects (funding, technical, risk)	▪ Lacks detail ▪ Model investment ▪ Cultural barriers ▪ Need to understand model's behavior	▪ Budgetary estimates ▪ Design-to-cost trade studies ▪ Cross-check ▪ Baseline estimate ▪ Cost goal allocations

Figure 24 - Detail on weaknesses and strengths of different cost evaluation methodologies [6]

The use of different methodologies during the different phases is a very contemplated practice, because it is possible to integrate more complex estimates to the simpler ones, going to evaluate also the order of cost magnitude.

The most used method, at the beginning of the aircraft design, is based in the first step on the realization of the Work Breakdown Structure WBS that represent the subdivisions of the categories. Such subdivision can be based on more levels and can be more or less pushed as level of detail.

For each element of WBS, will be developed the cost equation relationship (CERs).
This are statistical equations consisting of different coefficients generally linked to a design variable.
This technique is used to estimate a particular cost element by using relationships between independent variables, called cost drivers [ref.int 8].
CERs are measurable relationships between the independent variable and cost. Typically, they can have a form such as:

$$Cost_i = A_i * W_i^B * X_i^C * Q^K * CEF$$

where: Ai is a constant linked to the cost per kilogram of the different parts; W can represent the dimensional characteristics of the product (e.g weight); X is a characteristic of the component's performance (e.g. power, speed, etc.); Q is the quantity of parts produced, B, C, K are adaptive exponents; CEF is cost escalation factor.
Equations like this do not predict the actual cost of the aircraft, but give designers the opportunity to compare different alternatives and make the right decision to reach an "economic" product that can compete in the market.

2.4. Mathematical models for the Direct Operating Costs' evaluation

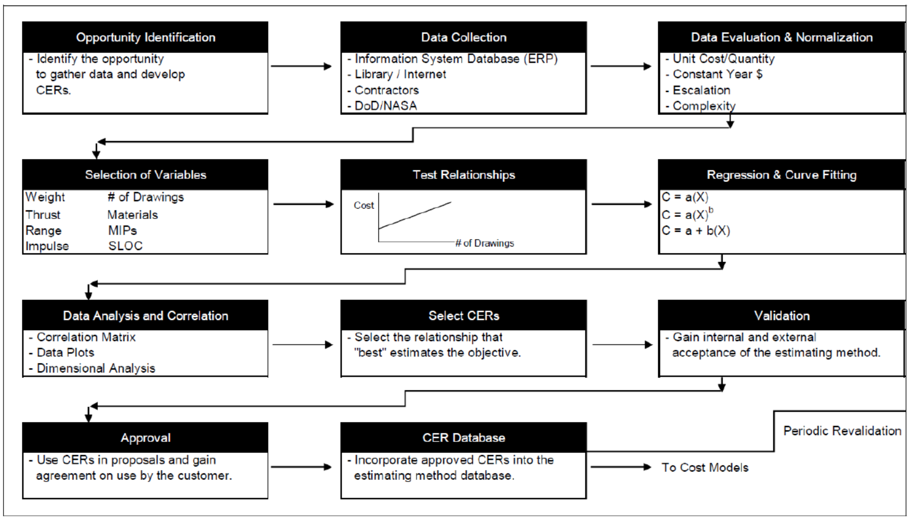


Figure 25 - Realization, validation and approval process of new model for the estimation of cost [6]

As mentioned above, the airline's profit increases if operating costs, in particular direct costs, are reduced.
For achieved this, it is necessary that designers go to develop aircraft taking these costs into account, with the aim of attracting more customers.
Going to assess the costs of a supersonic aircraft may not be easy. As we know, historically in the civil sector only two supersonic aircraft have crossed our skies (none of these were powered by liquid hydrogen).
The lack of information in this regard can make it difficult to compare with traditional aircraft operating mainly in the subsonic field.
Exploiting methods based on statistical analysts could lead to considerable errors. This, therefore, leads to the need to develop a mathematical model that fits well with this case by going to achieve a plausible estimate of direct operating costs, taking into account the main characteristics of a supersonic aeroplane powered by liquid hydrogen.
From the middle of the 20' century, some mathematical models were developed for the assessment of direct operating costs in the aerospace sector.

The main models still considered as a reference are:

- Standard method for estimating comparative direct operating costs of Turbine Powered Transport Aircraft (Air Transport Association of America, December 1967) [1]
- NASA methodology for planning hypersonic transport technology [2]
- Roskam [3]

The standard method of estimating the comparative direct operating costs of turbine-powered transport aircraft [1] is a basic methodology for estimating cost items developed by ATA (Air Transport Association of America) in 1967 [1]. This method is the first standardised method for assessing operational cost for subsonic jet aircraft.

This method is still today used as a reference basis for the development of other models. The proposed equations are updated annually by aircraft manufacturers.

Part VIII of Roskam Airplane Design [3] provides a methodology for assessing life cycle costs for both civil and military aircraft.
The methodology proposed in this text is based on the ATA [1] method and is used for traditional aircraft. Most of the equations proposed in this method are based on knowledge of the performance parameters of the aircraft and on some economic parameters.
The basic method uses some formulas to obtain values difficult to know, presenting data collection tables and characteristic curves for the various types of aircraft. All this gives the possibility of obtaining complex coefficients simply knowing the basic characteristics of the vehicle.

The NASA methodology [2] for hypersonic transport technology planning developed in 1973, has as base the ATA. This method going to readjust for high-speed aircraft operating in the hypersonic field for estimate the direct operating costs in relation to the technological parameters that such aircraft would introduce.
In this work, we would look at the latter model as the basis of reference.
However, not having been developed in recent times, it will be necessary to first update some parameters that are now being exceeded and go to readjust for supersonic aircraft.
It is of paramount importance to be able to use a model that lends itself properly to the estimation of costs.
The use of models that are not consistent or not adaptable to the case study can lead to incorrect results and in some cases also very discordant with reality.

3. Overview of Supersonic initiatives

This chapter will present the main aspects that characterize a supersonic aircraft powered by liquid hydrogen.
They will be briefly shown what are the most salient aspects of this technology and what are the studies to date carrying forward in this field.
Then, the typical mission profile of supersonic aircraft will be shown followed by a brief summary of a typical LCC for this category of aircraft.
Later, the main reference aircraft, existing and not, that have operated in supersonic field (fuelled by both conventional fuel and liquid hydrogen), will be illustrated.
In fine, the Green Concorde [7] will be introduced. This airplane, based on the studies lead from the students of the Politecnico di Torino, that it aims to demonstrate the feasibility in the adoption of the liquid hydrogen like main propellant for an airplane point-to-point supersonic with airbreathing engine and on which the analysis of costs will be based within the next chapters.

3.1. Introduction to LH2 power supersonic aircraft

This job focusses on supersonic commercial passenger transport powered by liquid hydrogen. This allows us to reduce the flight time and to reach increasingly longer point-to-point routes, with no need for stopovers and reduce the CO2 emission.
It was over a decade ago when the last civil supersonic aircraft could be seen airborne.
Since then, not only no passenger supersonic airplane has taken off, but also the development of almost all supersonic airliners has been terminated. After the pioneering era of the first supersonic aircraft generation, such as Concorde and the Tupolev (Tu-144), which were rather the result of the technology and prestige race among the world powers in the second half of the 20th century, aircraft manufacturers have mostly abandoned the idea of supersonic travelling, due to a broad range of issues related to supersonic transport.
Despite an indisputable progress in the field of aviation and aerospace, supersonic aircraft designers would still have to deal with significant technological, operational and legislative obstacles, often requiring complex and expensive solutions, which would mostly result in an economic un-competitiveness among other contemporary aircraft.
However, the interest in supersonic flight has never fallen and today there are many projects under development that try to overcome the technological limits of a few decades ago to bring commercial supersonic civil transport flight back to reality.

The Concorde made its first transatlantic crossing on September 26 in 1973 and it inaugurated the world’s first scheduled supersonic passenger service on January 21 in 1976. In that historical period, it was certainly a technological masterpiece, reaching a maximum cruising speed of 2179 km/h per hour with Mach 2.04, allowing the aircraft to reduce the flight time between London and New York to about three hours.
Despite this, the concord has never achieved the success its creators had hoped for.

Environmental and operational limitations of the Concorde hampered its commercial appeal among airline customers. Only 20 of the planes were ever built, and just 14 of them were production aircraft. The Concorde saw service with only two airlines on just two routes. The development costs of the Concorde were so great that they could never be recovered from operations, and the aircraft was never financially profitable.

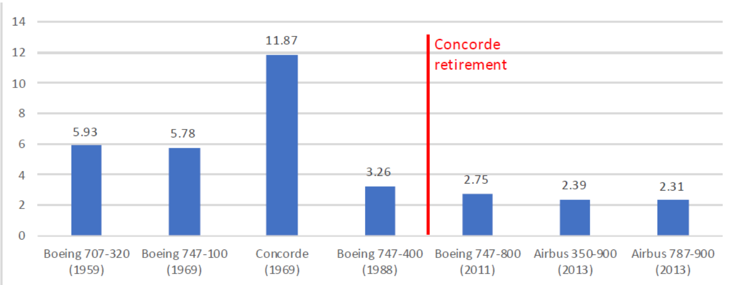


Figure 26 – Fuel efficiency per seat (litres/100 km) [7]

Beyond the high production cost, the problems of the Concorde consisted in the high consumption (about 13 litres/100 km per seat) and noise emissions, associated with the sonic boom. That is why Concorde planes were never permitted to fly at full and supersonic speeds over land (they were restricted to subsonic speeds on land).
In conclusion, the highly dynamic context of the air transport sector is driving the aviation industry to attain ever rising economic, environmental and social standards. A major challenge is to establish and develop the future of aviation beyond 2050.
This will involve the adoption of innovative air vehicle designs and systematic changes to the manufacture and operation of aircraft, including the type of fuel used, engine performance, weight metrics, air traffic management strategies and advances in safety.

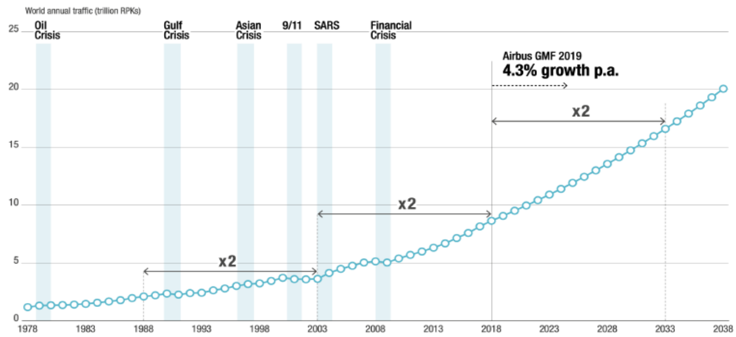


Figure 27 – Airbus RPK analysis - World annual traffic [26]

The average annual growth rate of passenger and cargo traffic, over the next two decades, is predicted at 4.4%, and this is a major driving factor promoting change in aviation. Furthermore, after the year 2042, it is expected that coal will be the only fossil fuel available, highlighting the importance of timely change and progress towards sustainable development.

One highly anticipated and promising alternative relies on the use of hydrogen (H2) as the main fuel source behind commercial aircraft engine propulsion due to its negligible environmental impacts so that achieve the decarbonisation aim.
At the meantime, the market's need for more efficient, reliable and high-performance aircraft is growing; therefore, in order to meet these new demands, in recent years supersonic aircraft projects are being carried out, improving the flaws that characterized the aircraft of the past and joining them the most recent technologies.

3.2. Mission profile of supersonic aircraft

The typical mission profile for a supersonic aircraft shown here is closely related to the Concorde.
Generally, routes requiring supersonic means cover long-distance points often crossing oceans or remote areas.
Generally, these routes and their relative heights are defined so as to avoid interference with subsonic air traffic.
The cruising altitude is generally between FL500 and FL600, which is an altitude at which changes in weather conditions have an extremely low influence that does not require a change of route.
The take-off of the aircraft generally happens taking advantage of the post burner in order to reach the speed demanded for the rotation and the take-off.
The take-off is followed by two phases, one climb and the other by subsonic cruise. Until clearance to proceed to the supersonic phase, the flight maintains a constant altitude and speed.
These two phases are necessary to reduce the acoustic impact of the shock waves (also known as sonic boom) over the ground and in particular on populated areas.
At this point, only when the aircraft reaches a reasonable distance from the departure airport, it can accelerate to reach supersonic speeds compatible with next phases of supersonic climb and cruise.
Subsonic to supersonic climb and acceleration are generally the most critical phases from the point of view of the skin temperature of aircraft. Taking the Concorde as an example, given the critical acceleration phase, the aircraft needed a clear corridor from the point where the afterburners were switched on to the point where they were switched off (phase no more than 15 minutes).
After the supersonic climb we find the phase of supersonic cruise that turns out to be the longest and most important phase of the flight.
At this stage, the cruising altitude is defined in an interval (usually between FL500 and FL600). This range is due to the fact that the aircraft operates on a parabolic trajectory (and not at a fixed altitude) with the aim of minimizing temperatures on the outer skin.
In fact, fixed the temperature on the skin usually the autopilot performs a trajectory dependent on the latter and not on the Mach.

After the supersonic cruise follows a descent phase.
The main objective of this phase is to reduce speed and altitude and at the same time reach values compatible with the next phase of landing preparation.

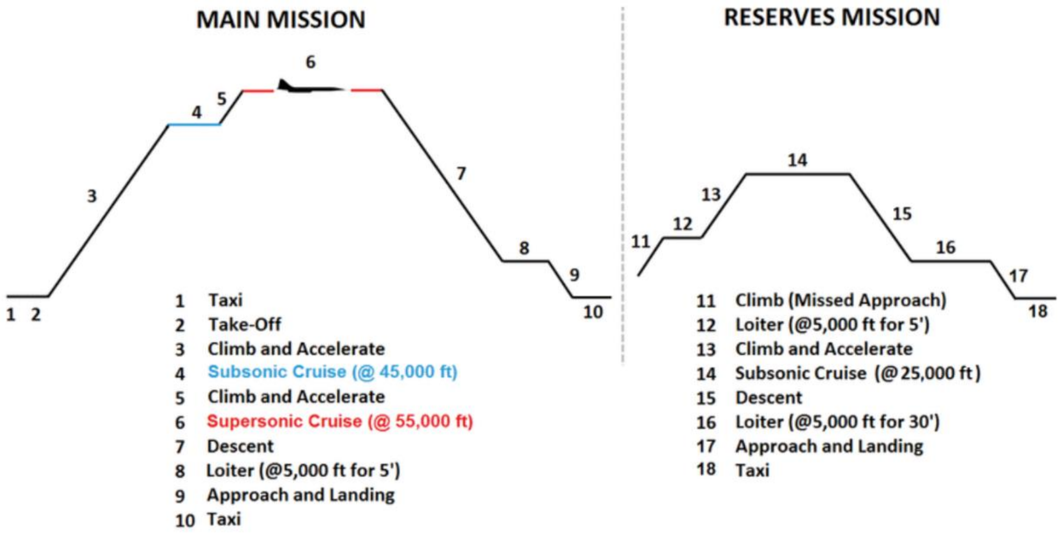


Figure 28 – Standard mission profile for combined subsonic and supersonic cruise flight [25]

The descent phase, in analogy with the climb phase, begins with a supersonic descent up to a certain altitude. This is done to avoid excessive losses in performance and fuel consumption. The descent phase also takes place until the vehicle falls into subsonic mode, showing itself as another critical phase to be carried out away from inhabited areas to avoid all problems related to shock wave phenomena.
The approach to the runway is divided into two different phases. One where the aircraft maintain the altitude for a short period of time and the other where the actual landing is attempted.
In the past, supersonic vehicles did not have the possibility to reschedule the landing at other destinations. Today, such a thing would be extremely limiting, for this reason, different solutions have been studied, in order to preserve an adequate amount of fuel to be able to perform a change of course or perform a landing at an alternative airport.
The landing phase can therefore be aborted at an altitude of about 200 m which must be followed by a rapid climb to an altitude sufficiently high to avoid any collision with obstacles on the ground. After this climb phase, the vehicle performs a short cruising phase at low altitude and then try the final landing phase.

In general, simply reducing the duration of the supersonic cruise phase, it is possible to increase the range of these aircraft or even increase the waiting times. In fact, its reduction will lead to a considerable fuel savings allowing precisely to reach other destinations or to reschedule a landing.

3.3. Cost estimation for supersonic aircraft

Current market analyses see how the growing number of global flights accompanied by an increase in per capita wealth bode well for the future in continued growth in the aerospace sector. However, the continuing growth trend in the aerospace market will lead to an increase in emissions that will necessarily have to be reduced through appropriate targeted strategies, including the use of alternative propellants such as liquid hydrogen.
Thanks to this propellant, have also developed ambitious studies operating in the field of high-speed flights to be able to cover market segments currently discovered (supersonic flights) or never occupied (hypersonic aircraft).

Currently, there are only several research programmes funded by various international sources which are considering the possibility of designing and building these new types of aircraft.
In general, for subsonic aeroplanes powered by liquid hydrogen, the cost-of-life items are the same as those of a traditional subsonic. What will change in part will be their value and their distribution.

The greatest challenge for supersonic aircraft will be to understand how the market will react to their introduction.
In the past, supersonic fuel-powered aircraft have lost interest when in a comparison with subsonic aircraft they have been result less economically advantageous.
As mentioned earlier, only a few aircraft models are powered by liquid hydrogen and most aircraft using this technology are still in the design phase.

The use of liquid hydrogen will lead to the development of new technologies in the aerospace field. The TRL (Technology Reediness Level) index is used to assess the maturity of a technology. This index, on a scale of 1 to 9, represented the evolution of technology from the first stages of research to full maturation and knowledge also during its use. For this, the introduction of liquid hydrogen technology, could lead to further studies and tests in phase of RDTE with consequent initial increase of the characterizing costs this phase (typical every time you go to introduce a new technology).
It should be remembered, however, that the costs relating to the RDTE are those which have a minor impact on the typical LCC, and the progressive increase in knowledge of this technology in the future will ensure that these items also adjust to more expected values. Therefore, it will be necessary, during the development, when the degree of maturity of the technology is still low, to invest the right number of hours in order to avoid that research leads to the choices not winning in economic terms or even potentially dangerous.
In conclusion, the costs of RDTE phases are almost comparable to those of a traditional aircraft, net of the extra use of designers for the study of the introduction of new technologies. Moreover, in order to avoid undesirable effects which may have an impact on costs during the production phase, it is also necessary that the production aspects are properly assessed during the RDTE phase.

As regards the cost of production, again, an increase in costs may be observed due to the introduction for certain add-ons and the effect of learning curve (the effect of this last one is more visible especially at the beginning of production, when volumes are still low). Analysing in more detail the aspects that characterize an aircraft powered by liquid hydrogen, we can immediately notice some differences from the traditional aircraft.
The use of this fuel in fact requires a bigger structure. In fact, a large amount of volume will be used to accommodate the large tanks containing liquid hydrogen.
These tanks must withstand temperatures of the order of -250 °C and for these reasons are made with specific materials that can ensure not only structural integrity but also a reduced thermal conductivity. This obviously leads to an increase in design and production costs compared to traditional aircraft.

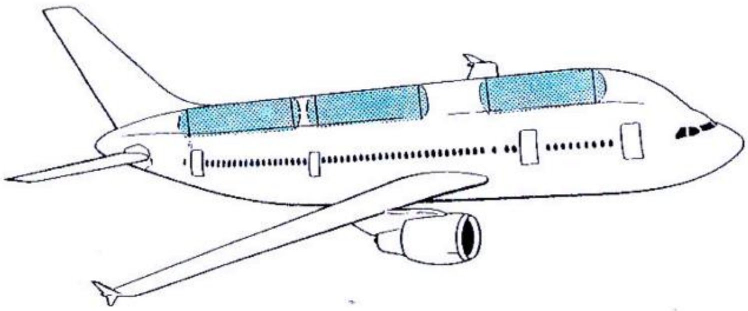


Figure 29 – Cryoplane representations, study of positioning liquid tank [12]

Like conventional aircraft, the operating costs of liquid hydrogen powered aircraft determine the success or otherwise of these aircrafts on the market. As mentioned above, a proper assessment of these costs from the early stages of the life of the project is extremely important. Unfortunately, hydrogen powered aircraft are not currently on the market (much less supersonic aircraft). So, it will be necessary to be able to extrapolate as much data as possible to interpret them correctly in part from existing supersonic conventional aircraft and in part from all the bibliographical references of aircraft that exploit liquid hydrogen.
Again, the focus is mainly on DOC, since the IOC do not depend on factors properly related to the design of the aircraft but more on external economic factors and marketing strategies. In general, is can expect that the indirect operating costs of a liquid hydrogen powered supersonic aeroplane are higher than those of a conventional aeroplane. For the instance, it can be ease suppose that although the dimensions of the means are compatible with the current aircrafts, part of the existing infrastructures will not be able to be employed for the logistic support of these means. This is mainly due to the fact that liquid hydrogen being a cryogenic fuel will need its own dedicated refuelling infrastructure. In addition, the use of this fuel can also lead to an increase in insurance costs to cover any damage to third parties or passengers.

As regard the maintenance, it shall be taken into account very carefully, especially during the development of technology. This aspect, if neglected, could lead to serious

economic damage to a company, forcing it to keep the vehicle on the ground too long and thus reducing the revenues resulting from its use.
A final aspect to be consider will be the salary of service staff (in particular flight attendants). Their salary, given the specificity of the mission, may be higher than the typical salary, but as we know, this aspect is linked to the contracts signed by the airlines and may not necessarily be different.
As far as fuel costs are concerned, it is not possible to define immediately a variation from conventional supersonic aircraft (having the same mission) because despite the higher price of liquid hydrogen compared to jet fuel, Liquid hydrogen fuelled engines require less fuel to be able to travel the same distances as conventional engines and thus reduce fuel costs.
So, in general for DOC all the elements change their value.
In the end you must also go to consider the cost of disposal. This should not be overlooked at all. Today it is unthinkable and absolutely unsustainable not to take into account the proper disposal of a vehicle. Given the high technological level of components, the first models to be disposed of could see an increase in costs. Also, in this case, like the other types of costs, the values of the cost of disposal should settle with time on expected values lower than those of the first units disposed of.

Wanting to summarize all those that can be the aspects that carry to a variation of the voices of direct operating cost (compared to subsonic aircraft) we find:

- Fuel cost: as we know, they are the largest item within the DOC. For supersonic aircraft due to their high SFC, the fuel consumption compared to conventional subsonic aircraft is much higher. This results in a considerable increase in the share of fuel costs within the DOC. In addition to increased consumption, an additional factor that tends to further increase the costs of this item is linked to the price of liquid hydrogen. This item as well as for oil is extremely volatile and it is difficult to predict its variability because the variables to be taken into account are different (source of production, country of production, market trends, economic policies, etc.);
- Personnel cost: in this case compared to traditional subsonic aircraft is expected to increase personnel costs given the most expensive mission in terms of work. However, an increase can be considered quite contained, and it should also be noted that this is one of the minority voices within the DOC;
- Maintenance costs: also, in this case, increases will be observed compared to traditional cases. It will be extremely important to pay attention to maintenance costs, as the adoption of a technology that is not fully mature or with components subject to a high failure rate (given the criticality of the application) may have adverse effects on the economic viability of the project given the increase in maintenance hours compared to flight hours.
  The increase in this ratio leads first and foremost to an increase in maintenance costs due to the greater number of interventions required to ensure safety of aircraft (as required by current legislation), and in second a reduction of the revenues due to the increment of the non-operativity of the aircraft. All this could potentially make the aircraft economically inconvenient;
- Depreciation cost: generally, the trend for this item is in slight increase, this is mainly related to the higher cost of acquisition of the aircraft. On the other

hand, the depreciation rate is not expected to increase due to a possible reduction in operating life.

Currently in the literature there are still few data to refer to aircraft of this type (especially data of an economic nature). This absence leads to an increase in difficulties in the development of a cost estimation model, since the estimated values cannot be compared with some real values that make it clear whether the model is functional or needs to be revised.

In addition to all aspects related to the design of the vehicle it is necessary to consider all the logistics that revolves around it. These aircraft should take advantage of existing airport facilities. To do this, it will be necessary for airports to adapt much of their infrastructure by upgrading their refuelling network (according to different LH2 demand scenarios airports may be required to have a hydrogen storage and liquefaction facility as well as a dedicated supply network for ground services), paying attention to all the risks that this new technology entails during ground operations.
Finally, it will be necessary to adapt the legislation for these means.

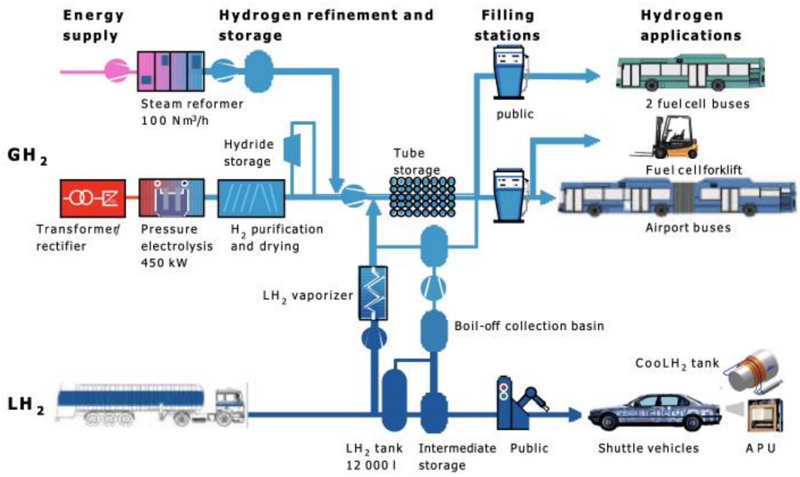


Figure 30 – Overview of the hydrogen project at Munich International Airport [27]

3.4. History of SST and Reference aircraft

In 1994, due to the complexity of the SST and the rapid increase in all the cost items characterizing these aircraft, an international agreement was signed for a common program that would determine the characteristics of a supersonic transport for the 21st century. Since then, in 26 years the program for the development of a second-generation SST (SST-2), numerous proposals have been observed.
From aircraft with characteristics of:

- MTOW 360 tons;
- carrying capacity of 300 passengers;
- range 8,000 km

has passed to more realistic requirements such as:

- MTOW of 260 tons;
- carrying capacity of 170 passengers;
- range between 7,000 - 10,000 km.

In addition, the possibility of adopting engines using liquid hydrogen as fuel has also been studied.
The results of the studies showed that an SST-2 should be able to compete with large aircraft such as Boeing B-747, B-777, Airbus A340 and A380 especially once reached high aerodynamic efficiency in both supersonic and subsonic modes, reducing fuel consumption and increasing autonomy, and consequently economic profitability.
These projects bode well for times when second-generation supersonic civil transport vehicles will fly into the skies.

As this thesis work focuses on the analysis of the operating costs of Green Concorde [7], a project developed just as SST-2, the next pages will illustrate some reference aircraft that are the basis of the development of this project, as well as some of the vehicles representing the first generation of supersonic civil transport aircraft (SST). Through these reference aircraft it was possible to carry out a small statistical analysis from which it was possible to define some of the starting parameters that characterized the design of the Green Concorde [7].
Their choice was based on some specific similarities to the Green Concorde and the mission to accomplish. To this, appropriate design choices have been integrated in order to avoid some of the major limitations characterizing first-generation aircraft and thus be able to correctly place it on the market.
All these reference aircraft could be useful also for the realization of a first useful database for the cost estimation during the initial phases.

Aérospatiale-BAC Concorde

Figure 31 - Aérospatiale-BAC Concorde [28]

Production of the Concorde began in 1966. The first two prototypes never entered service but served only as a test bed for production techniques and further developments. Concorde's final tests only began in 1974.
Only British Airways and Air France purchased the Concorde and the vehicle became officially operational on 21 January 1976, completing as main routes those between: Paris - Dakar - Rio de Janeiro, London - Bahrain and London/ Paris - New York.
The budget for the construction of a Concorde went from 9 million $ in 1969 to 25 million $ in the late 1980s, with a peak of 40 million $ in 1977 (being six times more expensive than expected). This resulted in a reduction in production to only 20 units compared to the 500 planned.
Maintenance of the aircraft lasted between 18 and 20 hours per flight hour, compared to the 2 hours used on average for other airliners, and its cost per hour of flight in the early 1980s was about 44 thousand dollars.
In addition, the impressive fuel consumption (an average of 17 litres per passenger per 100 km) was a relative problem before the oil crises of 1973 and 1979, which led to a large increase in the fuel prices. Obviously, all this led to a considerable increase in the cost of the ticket, resulting three times higher than a first-class ticket of a normal airline. This ended up making the Concorde an aircraft for the exclusive use of VIPs. However, his technical equipment was extraordinary.
Starting from the wing, the aircraft was equipped with a delta-ogival wing designed to ensure the best possible performance at high speed.
There were no horizontal control surfaces except for wing ailerons that guaranteed longitudinal and lateral-directional stability and control. These aerodynamic characteristics led to high attack angles demand during take-off and landing manoeuvres.

To ensure that these flight phases were safe, the engineers provided the aircraft with a variable nose angle to ensure sufficient visibility for the pilots.
The Concorde was equipped with 4 Olympus 593 turbojet engines, designed to support a supersonic cruise even without the use of afterburners (allowing a reduced fuel consumption during the cruise). The 4 engines were positioned under the wing surface and were equipped with air intakes with variable geometry to ensure the best performance during supersonic flight.
The serious deficit accrued by Concorde in the years of exercise brought the plane to be included in the list of the so-called "white elephants". This is an expression in France and the British countries which refers to projects or assets whose implementation and management costs are not offset by the benefits they provide.
Among the various factors that led the decision of give up the project there's been the deficit due to the impressive operating costs due to maintenance and fuel consumption and the only, but disastrous, accident that occurred on 25 July 2000.
On 24 October 2003, passenger service ceased, and the last flight was on 26 November 2003.

3.4.1. Tupolev TU-144

Figure 32 – Tupolev TU-11 [29]

The Tu-144 was the world's first supersonic civil transport aircraft. On July 26, 1963, it began its development phase with a program that included the construction of five prototypes by 1966. The first prototype appears was profoundly different from the remaining specimens. On 31 December 1968 (two months before Concorde) the first prototype was flown.
The first supersonic flight was conducted only on June 5, 1969 (four months before the Concorde) and on May 26, 1970 became the first commercial transport aircraft in the world to overcome Mach 2.

The end of production occurred in 1983 (well five years after its removal from use as a civil transport aircraft) with only 16 aircraft-built.
The Tu-144 conducted 102 commercial flights, of which only 55 carried passengers, at an average service altitude of 16,000 meters and sailed at a cruising speed higher than Mach 2.
To date, it holds the world speed record (Mach 2.50) for a civilian aircraft.
Western newspapers dubbed the plane Concordski, to emphasize the strong similarity with the Anglo-French aircraft (there were however significant differences between the two media).
The Tu-144 is larger and faster than Concorde (M2.15 vs M2.04).
The Concorde used an electronic engine control package from Lucas, which Tupolev was not allowed to purchase for his Tu-144 as it could also be adopted on military aircraft.
While in the Concorde the fuel was also used as a coolant for air conditioning in the cabin and for hydraulic system, the Tupolev used specific cooling turbines for cabin air and fuel/hydraulic heat exchangers for hydraulic system.
As for the wings, the first Tupolev model adopted an ogival delta shape similar to that of the Concorde but which was later replaced in the production models with a double delta wing. Were also added two small retractable surfaces called a “moustache canard”, with fixed double-slotted leading-edge slats and retractable double-slotted flaps.
Despite these technical solutions, the Tupolev’s landing speed was considerably higher than that of the Concorde, that had by its greater optimization of the wing profile at low speeds.
The main reasons that led to the cancellation of the program are mainly related to its high rate of failure and the development of a single trade route Moscow - Alma-Alta. In fact, the flights were limited to one per week (despite the eight certified vehicles available).
The request of the Soviet government officials to limit the available flights and reservations due to the high rate was a valid move. Their decision is also based on minimizing the possible impact of image and the political repercussions due to possible technical accidents.
Bookings were therefore limited to about 70-80 passengers or less per flight (well below both the seating capacity). On its 55 scheduled flights, the Tu-144 have carried a total of 3,194 passengers, with an average of 58 passengers per flight. This led to proven economic inefficiency, supported by rising fuel prices and replacement with other commercial aircraft.

3.4.2. Boeing 2707

The Boeing 2707 was a supersonic aircraft developed by Boeing in the 1960s.
Following the 1962 announcement of Anglo-French cooperation for the construction of Concorde and the launch of the Soviet programme for Tupolev Tu-144, the United States found itself without a similar programme for the construction of a civil supersonic transport aircraft. Only in 1963 they launched the development program (75% funded by the United States government).

However, Boeing began a study of supersonic transport aircraft as early as 1952, but it was not until 1958 that a permanent research group was set up within the company, which in 1960 had an annual budget of 1 million $.

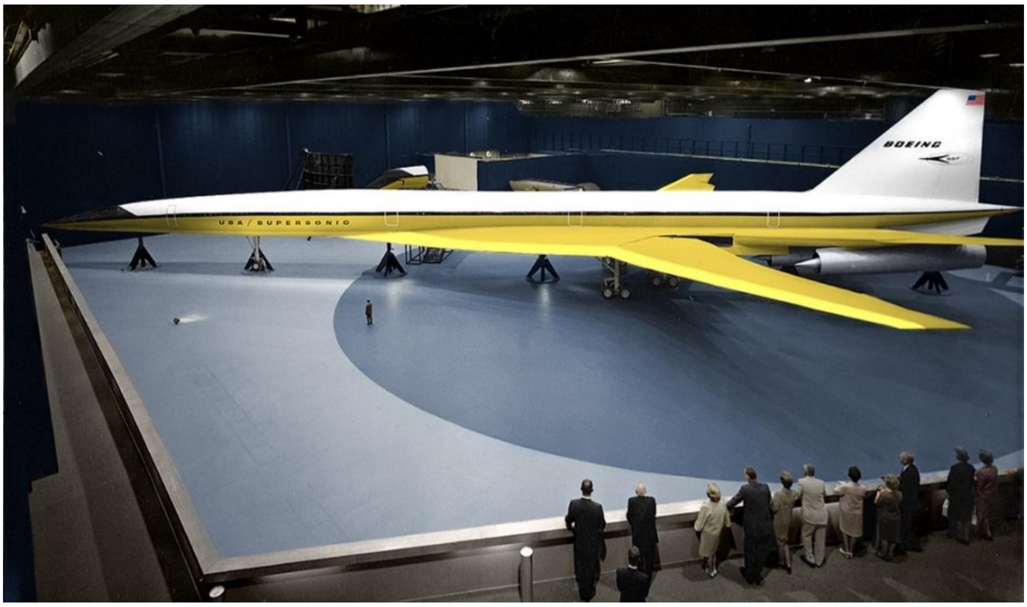


Figure 33 – Boeing 2707[30]

The first solutions were proposed, all under the name of Model 733. Most projects involved the use of delta wing, but, in the wake of the success of the variable geometry wing in the Tactical Fighter Experimental Program (TFX), it was decided to favour (with the Model 733-197) the development of a 150-seat aeroplane for transatlantic routes with variable geometry wings.
After a first development phase in 1966 the FAA moved to the next phase of the race that saw the Boing competing with the Lockheed CL-823. In September 1966, Boeing and Lockheed presented the full-size mock-ups and performance details of their models to the FAA (Model 733-390 and L-2000 respectively). On December 31, 1966, after a careful analysis of the FAA declared the Boeing project the winner, considering that the Lockheed was easier to build and less problematic, but with lower performance and greater acoustic impact.
However, following the emergence of various technical problems, rising development costs, and uncertainty about economic return, Boeing was forced to substantially revise the design, eliminating the variable-geometry wings and returning to a simpler configuration. In addition, public concerns about the environmental impact led the US Congress to cancel its financial commitment to the SST (Supersonic Transport) project. In 1971, the program was finally cancelled before the two prototypes were completed.
Prior to the closure of the project, the Boeing 2707 had collected 122 orders from 26 airlines. The two prototypes were never completed and, due to the loss of government contracts and the downturn in the civil aviation market.
This is a clear example of how the world of aviation costs can be greatly influenced by external factors. All this led Boeing to lay off 60,000 employees to prevent the closure of the company.

3.4.3. Lockheed L-2000

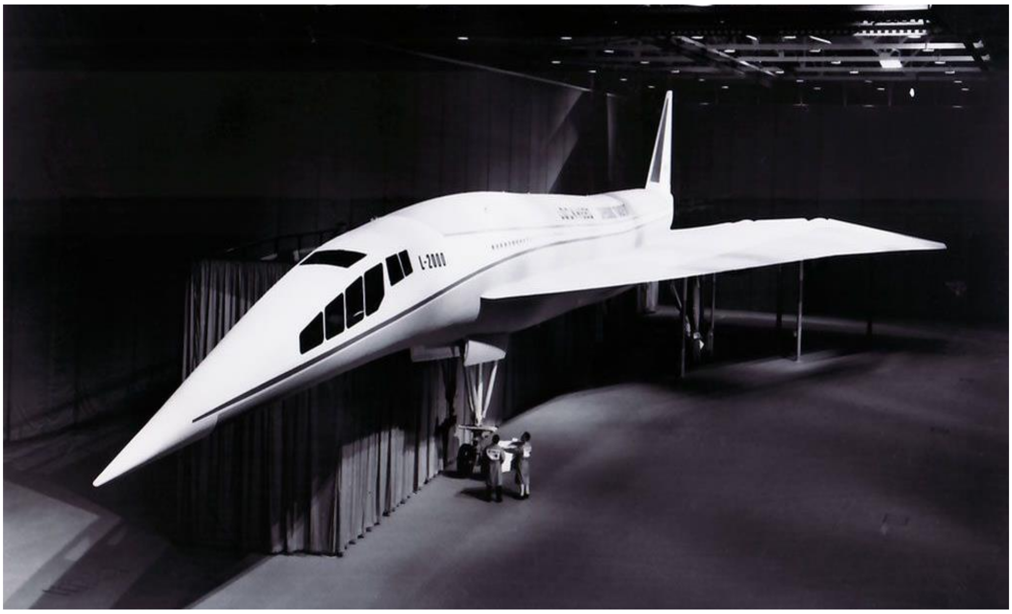


Figure 34 – Lockheed L-2000 [31]

The Lockheed CL-823 was been a competitor of the Boing 2707 in the race promoted in 1961 by the United States government for the development of a supersonic transport aircraft (SST). The race was won by the Boeing 2707 despite the Lockheed design was judged simpler and less problematic to construction, but with lower performance in take-off and at low speeds. Few years later, the Boeing's project was cancelled for political, economic and environmental reasons.
The program was launched on June 5, 1963 (in those years the FAA supposed a market of 500 such aircraft by 1990).
Like Boeing, Lockheed began studying solutions for SST already in the 1950s. The competition included in addition to supersonic performance in cruising also landing speeds equal to those of subsonic aircraft and the objective of controlling the pressure centre throughout the entire speed range.
The Lockheed as Boeing had assumed a first solution with to variable geometry wings but well soon the disadvantages in terms of weight and constructive complexity, they made them opt for a fixed wing solution and a possible use of the fuel as movable ballast in flight.
The first wing designated by Lockheed involved the use of a trapezoidal geometry with the addition of two canard wings. Subsequently, given the low performance results obtained in the wind tunnel, the use of the delta wing with "drowned" engines in the wings was considered. Finally, in 1963 the wing was modified a further time adopting a double delta design with high arrow angles and the engines were then repositioned in specific gondolas under the wings.
To ensure acceptable commissioning times, Lockheed opted for a version derived from the Pratt & Whitney J58 turbofan (mounted on the SR-71).
In 1964, the United States government modified the specifications of the SST program forcing Lockheed to modify the project, now called L-2000-2.

In 1966, the project took its final form with versions L-2000-7A and L-2000-7B. (respectively from 83 / 89 meters for the transport of 230 / 250 passengers in a mixed configuration of classes). The maximum take-off weight was 267 tons and the maximum aerodynamic efficiency was 7.94. Only a life-size mock-up was made of this aircraft.

3.4.4. Tupolev TU-244

Figure 35 – Tupolev Tu-244 [32]

The Tupolev Tu-224 was a prototype supersonic aircraft, developed by improving the Tupolev Tu-144. Designed to travel 10000 km using cryogenic fuel and carrying up to 320 passengers by 2025.

Already, in the early 1970s, the Tupolev OKB began work on a second-generation supersonic transport, SST-2.

Its design began officially in 1979 (a year after the withdrawal from service of the Tu-144) and was officially cancelled in 1993.

Although the Tu-224 was not built, great studies were made to reduce aerodynamics drags during flight to Mach 2.

The entire fuselage and wing attachment had to be composed mainly of composite materials and titanium while the four Kuznetsov NK-engines32, should have had high performance and low fuel consumption (powered by cryogenic fuel).

In term of design, the most evident difference between the Tupolev Tu-224 and the Tupolev Tu-144 is the nose. In the Tu-144, the nose could be tilted to give pilots a better view during landing. In Tu-224 this possibility was given by special cameras placed on the nose of the vehicle.

The design of the new aircraft had to be oriented towards increasing points such as: economic profitability, flight autonomy and passenger comfort. In addition, second-generation vehicles should have complied with the new ecological rules and become more competitive versus subsonic aircraft.

3.4.5. LAPCAT-A2

Figure 35 – LAPCAT A2 [33]

The A2 LAPCAT configuration is one of the design studios parts of the program LAPCAT (Long-Term Advanced Propulsion Concepts and Technologies) of the European Union, for a long-haul and high-capacity ecological civil transport aircraft developed by aerospace engineering company Reaction Engines Limited.
Used within the programme as a reference for the assessment of operational costs.
The company says that a functional model could be built in 25 years if market conditions are favourable. Its cost is estimated to be 639 million euros for a production of 100 aircraft.
The vehicle is designed to have a range of about 20,000 km and good fuel consumption at both subsonic and supersonic speeds, thus avoiding the problems inherent in previous supersonic aircraft, a higher maximum speed (Mach 5) and ability to land and take off from existing airports.
In addition, the vehicle uses liquid hydrogen as a fuel, also used as a coolant for both the aircraft and the air in inlet to the engines.
The developers say that it would be able to fly from Brussels to Sydney in about 4.6 hours and that the cost of a ticket should be equal to a business class ticket for a normal subsonic aircraft.
Due to the high heat flow generated at the hypersonic cruise speed, the A2 design is windowless. To avoid problems related to psychological factors of the passengers, the developers decided to mount inside the fuselage of the flat screens to show the images of the external environment.
Scimitar engines use the company's engine technology SABRE (intended for space launch), but adapted for long-distance travel at very high speeds.
This engine is a high by-pass-ratio (4:1) Turbofan with good efficiency and a subsonic exhaust speed which makes it pretty quiet.
One of the key features of this engine is the use of a pre-cooler, that is, a heat exchanger placed after the air intake that transfers the heat from the air at the engine inlet to the cryogenic fuel.

3.4.6. LAPCAT-MR2

Figure 36 – LAPCAT MR2 [34]

Like the previous aircraft, the LAPCAT MR2 project started in 2005 under the leadership of ESA-ESTEC, which coordinated twelve partners between industry, universities and research centres.
In this case, since the aircraft designed to travel at hypersonic speeds had to be equipped with special technologies both for the propulsion system and for the aerothermodynamic. To achieved this, part of structural design of the vehicle must be performed in combination with engine design introducing advanced propulsion concepts and aerodynamics dedicated to hypersonic regime (Wave rider design).
The LAPCAT MR2 is considered to be an LAPCAT A2 evolution, but it was not chosen as a benchmark vehicle for cost analysis.
As like LAPCAT A2, here too the mission of reference is conducted between Brussels and Sydney, stacking this time a shorter flight time (about 2:55 hours) flying at a cruising speed of MACH 8 and at an altitude of the cruise of about 30-35 km.
The LAPACT MR2 is equipped with special engines able to for both high supersonic flight (Mach $\leq$4.5 exploits ATR engines - Air Turbo Ramjet) and hypersonic flight (4.5<Mach $\leq$8 exploits DMR engines - Dual Mode Ramjet) with a single intake. As in LAPCAT A2 also in this case, the fuel used is liquid hydrogen. Being LH2 a cryogenic fluid it is possible to use its boiling steam to cool all critical parts of the structure.
The aircraft is also equipped with a sophisticated thermal energy management system that allows to cool the passenger cabin by exploiting the physical properties of the fuel.
In 2006 a first cost estimate for MR2 was conducted. The total cost of the overall development reported was expected to be 22,6 billion euros (of which more than a third were related to engine development alone). It was considered a production of 100 units with an average selling price of 639 million euros for each vehicle and the operating cost is estimated at 553.8 million euros per year of which the largest seems attributable to the cost of fuel (83% of DOC).

3.4.7. NASA supersonic aircraft concept powered by LH2

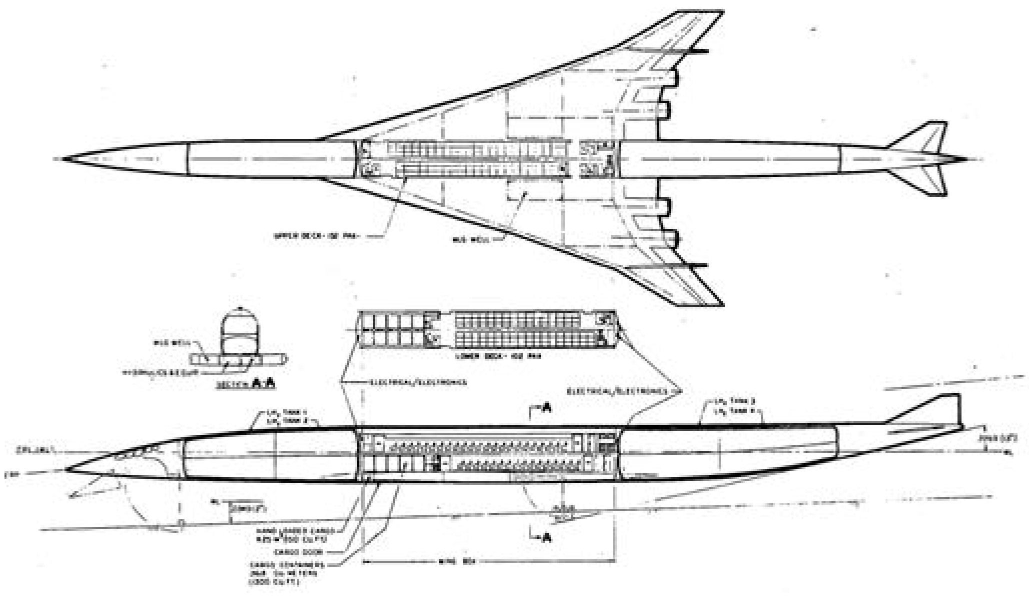


Figure 37 – NASA LH2 SST concept [16]

In figure 38 is show a NASA study for supersonic aircraft [16] powered by liquid hydrogen conducted in 1973. The aim of the study was to explore the economic potential and performance of liquid hydrogen powered supersonic commercial transport aircraft and to compare with an equivalent aircraft powered by Jet A-technology

The study was conducted in two phases. During the first phase, an exploratory analysis was conducted to parametrically identify the potential of a large number of different configurations of LH2 powered vehicles, all this in order to determine a preferred concept design and design requirements.

Several LH2-powered vehicle designs were evaluated.

The design basis and criteria were selected to provide a direct comparison of design, performance and cost characteristics between an LH2 powered civil transport aircraft and a jet fuel powered equivalent design aircraft.

During the second phase, a more specific analysis was carried out to obtain data and parameters on the configuration with a higher level of detail than phase 1. In addition, was studied important data related to the mission of the aircraft, the benefits and costs associated with it.

Various engine configurations (turbojet and turbofans) were evaluated and the study showed that turbofan engines were more optimized for flight up to Mach 2.7.

The set of parameters such as the thrust/weight ratio and the wing load (W/S) were determined, which would have produced the most advantageous means of carrying out the mission with less weight, lower consumption and lower cost.

At the end of the second phase it was possible to obtain a single design for the aircraft that best represented the requirements obtained by the studio.

3.5. Green Concorde

Figure 38 – Green Concorde [7]

The project of Green Concorde [7] was born in 2019 within the Polytechnic of Turin. Developed by a team of students as part of course of "Project of integrated aerospace systems", it was created to address issues related to the preliminary development of an environmentally sustainable aircraft in the coming decades, able to exploit liquid hydrogen as main fuel and that it was able to transport people in different areas of the world in a few hours through a supersonic cruise speed.
The study began through the collection of data of some reference aircraft that were suitable for the generation of a small database from which to perform a statistical analysis and thus derive some of the initial parameters such as: MTOW, Swing, Wing loading, Static net thrust and Propellant mass fraction.
In order to succeed in correctly estimating the weight of high-speed aircrafts during the initial phases, it is necessary to use as driver the speed of cruise (and not the mass of the payload as is generally done) as the latter would have significantly affected the architecture of the vehicle and engines. Only once got MTOW you should be able to estimate the mass of the payload.
As a result of this, to be able to define well in conceptual field the new design that this hypothetical new aircraft should have had. A trade-off was carried out based on drivers and figures of merit that defined the configuration on fuselage, type of wing, control surfaces and type of propulsion system. Then, through a matching chart and a configuration evolution step, it was possible to reach a final design with some key dimensional characteristics that referred to the initial requirements and to the requirements of regulation (CS-25).
As an external configuration, the aircraft looks very similar to what already seen in the first-generation SST aircraft but more refined.
The realization of the main structural components has been realized with specific materials able to resist to the aero-thermodynamic loads that arrive during the

mission (max temperature on the wall during the supersonic cruise is of about 150 °C).

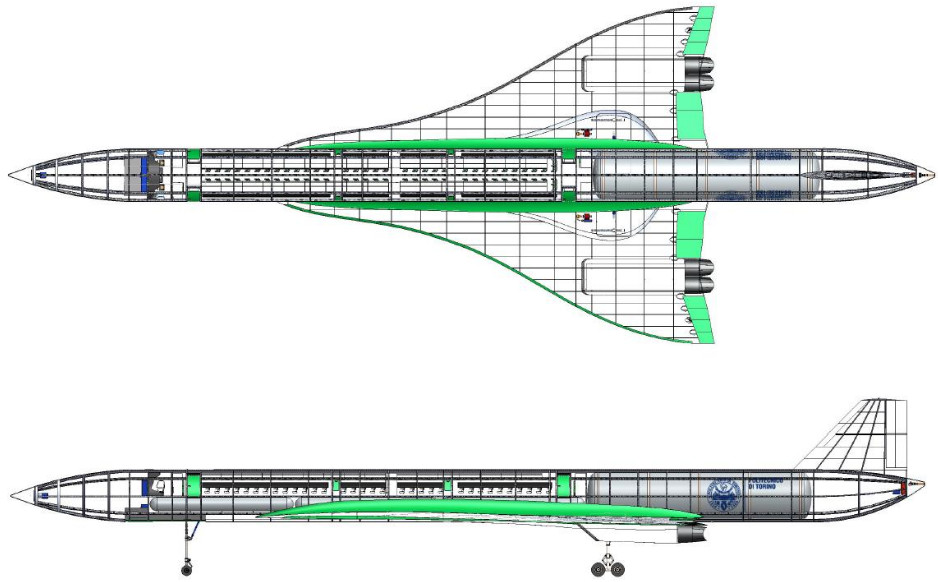


Figure 39 – transparent view of the interior of Green Concorde [7]

The aircraft was built mainly using aluminium alloys, composite materials and titanium alloys.
Also here, there is a configuration of the control surfaces such as those present on Concorde, in fact to ensure a reduced resistance of the aircraft (reducing the terms related to the induced, wave and friction drag) and improve aspects related to aerothermodynamics the only horizontal planes introduced are related to the wings.

Wetted area estimated	1191.09 m^2	Lift coefficient take off	0.69
Oswald factor	0.85	Profile drag coefficient	0.03
C_f	0.0015	Glide ratio in take off configuration	8.67
Mission type	Best range	Climb gradient ($\geq$ 0.024 for FAA)	0.03
Range (>8000km)	9000 km	Thrust to weight ratio	0.19
Cruise speed (M>2)	2209 km/h	Thrust per engine [kg]	18992
SFC (cruise)	0.6 kg/hour/kg	Thrust to weight ratio	0.52
SFC (with afterburner)	1 kg/hour/kg	Wing weight	17696.17 kg
E (supposed)	18	Tail weight	1769.67 kg
Fuel weight	23600 kg	Fuselage weight	25870.91 kg
Fuel % during landing	5 %	Installed engine weight	15000 kg
Take off duration	30 s	Gear weight	6607.58 kg
SFC (TO)	0.4 kg/hour/kg	Total empty weight	106590.30 kg
Throttle during climb	95%	Fuel Weight	23600 kg
Absolute Ceiling	18500 m	Payload	24750 kg
SFC (climb)	0.5 kg/hour/kg	Take off weight	154836 kg
RC at Absolute Climb	300 ft/min	FCS	3670.88 kg
Max turn load factor	2.8	Hydraulic system	1468.3 kg
Turn altitude	4000 m	EPS	7341.75 kg
Turn speed	650 km/h	Fuel system	2936.7 kg
Wing area	518.57 m^2	Air conditioning	11746.81 kg
Sweep angle	24.5°	Avionic system	4405.05 kg
Cruise mach	2.2	Engine system	2202.53 kg
Thrust per engine	11723.88 kg	Furnishing system	5873.4 kg

Figure 40 – Green Concorde data and performance [7]

These are equipped with all the control surfaces to govern the aircraft in the longitudinal plane, while the control of the directional lateral plane is delegated to a single vertical rudder.
Here, the wings were designed to ensure not only good performance during the cruising phases, but also to improve what were the limits of previous designs going to improve the manoeuvrability performance, of aeroelasticity and aerodynamic efficiency in supersonic field.
The introduced design was an "Ogival delta-cranked" wing, equipped with high sweep angle (typical of supersonic aircraft), a dihedral angle to improve supersonic performance and a geometric/aerodynamic twist angle starting from the half of the wingspan up to the tip. Between the wing and fuselage, in order to minimize the effect of the interference drag, was introduced a cine, and at the bottom was introduced a belly to accommodate the main landing cart.
The fuselage was designed with the aim of improving the performance of the vehicle in different aspects and being able to resist at the various loads correctly.
Its geometric design (cylindrical section, elongated and not excessively narrow) aims to mitigate the effects of the sonic boom, reduce wave drag and above all, provide a comfortable environment for passengers and to accommodate the large LH2 tanks.
To improve its performance, a windowless design was adopted. This design, representing the future trend of aviation, offers many advantages in terms of performance (reduction of discontinuities of materials, improvement of the distribution of loads, reduction of crack start points) and also in terms of costs (reduction of hours of operations and materials required for the construction of windows and reduction of maintenance costs related to the latter again in terms of both working hours and material).
However, its greatest limiting factor is the psychological factor in passengers. Flying in a closed environment without the possibility of seeing outside could generate claustrophobia and negative considerations in passengers. This, could bring to a limiting consequence in terms of ticket sales and consequently on the market. For this reason, in order to overcome this problem inside the vehicle, a suitable system of vision of the external environment has been set up, based on the projection of the images on curved OLED panels arranged along the entire length of the fuselage.

Figure 41 – concept of future infotainment system in a windowless aircraft [7]

The only notches in the fuselage (arranged symmetrically in relation to longitudinal plane) are relative to the exit doors, emergency exits and two windows in the cockpit present for safety reasons.

The interior of the fuselage was made in 5 separate blocks:
Habited section - located in the upper central section of the fuselage, is the only section equipped with an environmental control system control system. This section includes, cockpit for 2 flight crew members (pilot and co-pilot), the passenger cabin in which there are 198 seats for passengers (arranged in 33 rows of 6 seats arranged symmetrically on both sides) with its overhead bins for hand baggage, 4 seats for cabin crew, 4 toilets, 2 galleys.
Tank section - divided into 2 parts, in which a first is placed below the floor of the habited section, containing 3 refill tanks. While, the second, containing the main feed tank, is placed at the end of the habited section and occupies all the internal diameter available in the fuselage. Being their main purpose to house the large cryogenic fuel tanks, they are separated from other environments to avoid problems due to thermal exchanges.
Cargo Section - divided into 2 parts, placed in the tail cone and at the tip. It serves to contain the volume of the passengers' main baggage or other objects to be taken on board.
Plant section - divided into several parts, with the aim of hosting all of the subsystems and related elements present on the aircraft such as the avionics or part of the power supply system.

Figure 42 – Green Concorde rendering on the Atlantic Ocean [7]

As for the propulsion system, this consists of four turbofan engines with post-burner mounted below the wing planes in two dedicated gondolas and able to provide the maximum thrust values of 800 kN (required by the first statistical analysis) and at the same time, to reduce the fuel consumption used during the flight (using 85% of the throttle during the cruising phase).
It should be noted that, the introduction of the afterburner despite considerably increases consumption, is necessary to increase the maximum thrust generated by the aircraft and required at some phases of the mission.

So, this kind of engine allows you to operate in the whole range of conditions required while maintaining a good level of performance, an acceptable fuel consumption, and at the same time, minimize the complexity of the system. In addition, this propulsive solution is well known and widely used, which facilitates the passage of fuel from hydrocarbons to liquid hydrogen, thus avoiding excessive increases in maintenance costs of this element.
As far as the propellant system is concerned, this one, as previously described, is made up of 4 large tanks of liquid hydrogen.
The application of this type of fuel has been studied for more than 50 years in many fields. Its strengths are in the total zeroing of CO2 emissions, a reduction of up to 80% of NOX, an increase in water vapour production of 150% and a reduction of the climate impact ranging from 50 to 75% [39].
The liquid hydrogen has a density of 71 kg/m3 at the temperature of -252.87 C and

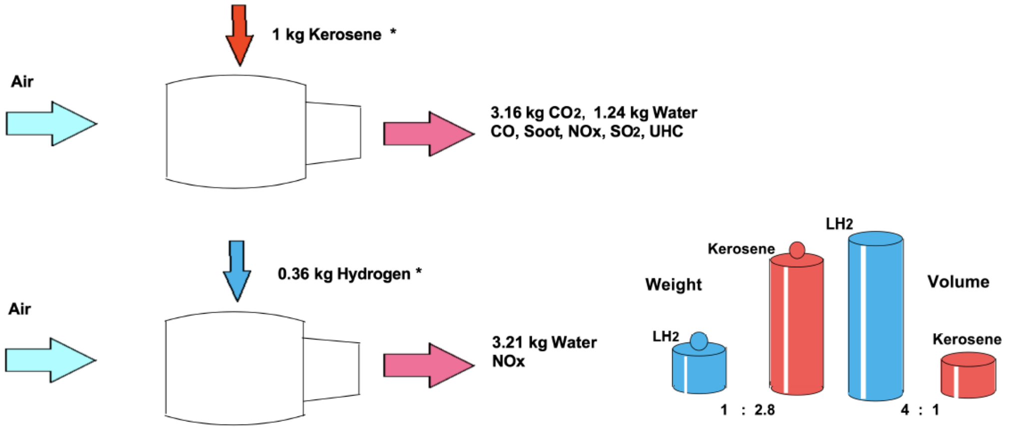


Figure 43 – Comparison between combustion products of liquid hydrogen and kerosene [12]

at a pressure of 1.013 bar, also has an amount of internal energy per kg about 2.8 times greater than that of kerosene, thus leading to equal energy value required to achieve significant savings in terms of weight. However, part of this advantage in terms of weight is lost due to low density of this fuel which leads to required large volumetric tanks capacities, resulting disadvantage especially for aircraft operating at high speeds speed.
The operating temperatures at which the fuel is to be stored, shall be such as to ensure the structural part of the tanks is suitably dimensioned for the selection of materials and capable of withstanding the loads and which do not exhibit the phenomenon of fragility due to at low temperatures. In addition to this, the tanks must also have a suitable insulating part, designed to be as performing as possible in avoiding heat exchange with the outside, thus maintaining as much as possible the fuel temperature throughout the mission and avoiding the boil-off phenomenon.
Inside the tanks there are also some anti-sloshing bulkheads to prevent the rapid movement of the fuel contained inside.
In addition to the tanks, all the other elements of the propellant system are designed with the aim of being able to operate at cryogenic temperatures.
To avoid the phenomenon of ice formation that could occlude the orifices inside the plant, it is necessary to conduct operations to remove air and moisture from tanks and lines with helium and create a vacuum before introducing LH2.

It is important to pay attention to the fact that a mixture of LH2 and solid oxygen or solidified air can explode.

As for the flight mission, this is based partly on the one carried out by Concorde, but going to overcome the problems of the latter. The mission of Concorde was to join two cities (London-New York) flying over ocean routes at an altitude between FL500 and FL600 avoiding interference with subsonic air traffic and atmospheric phenomena.

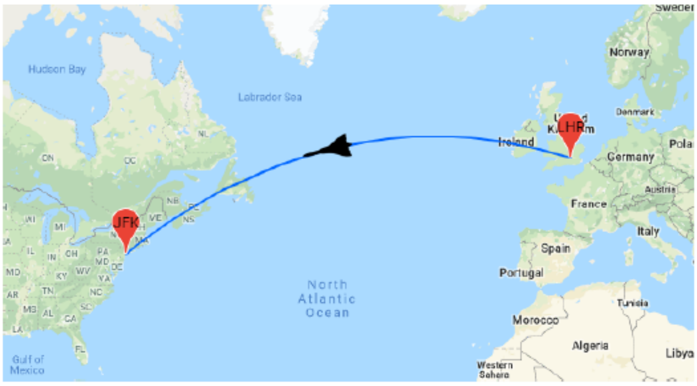


Figure 44 – Green Concorde route (London – New York) [7]

The distance between these two locations is about 5500km, compared to the 8000km range for which the aircraft was designed. This allowed to solve one of the great weaknesses of the Concorde, bringing the total waiting time of 10 to 35 minutes.
If would like take more advantage of flight range is necessary reduce the waiting time (always at acceptable values).
The route London - New York was chosen not only for this reason but also because is considered economically interesting, as well as being the only one of which it is possible to trace real data for civil supersonic flights and which lends itself well to the complex legislation currently in force.
The study was conducted through the ASTOS. The study of the mission with this software starts from the moment when the plane in acceleration phase detaches from the runway (minimum length of 3000m). Here the aerodynamic configuration of the vehicle (designed to fly in the field supersonic) provides that take-off takes place with a considerable angle of attack to generate the necessary lift vortex to face the first subsonic phases. It should be noted that, this high angle of attack has a considerable influence on the height of the landing gear and the seat angle of tail cone.
The take-off phase is followed by a subsonic climb and a small subsonic cruise. These phases are necessary to reduce the acoustic impact of the sonic boom on the ground, especially in populated areas. Only when the aircraft reaches a reasonable distance from the last inhabited point does it begin to perform the supersonic acceleration required for the supersonic climb and the subsequent supersonic cruise phase.
The latter, is the longest phase of the flight and has been calculated trying to achieve the maximum range possible while maintaining a residual amount of fuel that can provide the ability to land at an alternative airport.
After supersonic cruise, there is a phase of descent. This phase aims to progressively reduce both speed and altitude making them compatible for the approach and

landing phase. This must necessarily cause the sonic boom to happen again far from habited areas.
If an alternative landing is to be tried, the landing procedure is cancelled after reaching 200 m of altitude followed by a rapid climb to altitudes high enough to avoid obstacles or any collision and a short cruise conducted at low altitude until new approach and final landing.
Here the length of the track required once the touchdown has been made must not be less than 1830 m.

4. Presentation of cost estimation model

In this understanding will be presented the model that will serve as the basis for the estimation of costs for this work.
The methodology for estimating costs proposed by NASA in 1973 [2], based on the 1969 ATA method [1], for the calculation of direct operating costs for hypersonic civil transport aircraft, will then be presented.
This method, used in the past for estimating the costs of hypersonic aircraft, may be partly adapted to the present case, since some of the technologies examined here, such as the use of cryogenic fuel or the use of airbreathing engines, are the same as those on the reference aeroplane.
Obviously, it will be inevitable to go to analyze and adapt in case the equations present to the case of SST aircraft powered by liquid hydrogen.
It will then be shown a detailed description of this methodology, reporting what is the basis used by the model. The CERs for each item of direct operating cost with the relative coefficients and the present technological drivers analyzing the most important aspects of these equations.

4.1. NASA cost estimation model for hypersonic aircraft introduction

The objective of the NASA study [2] is to develop a methodology to assess the influence of technological factors on the design, configuration and operation of a hypersonic transport aircraft (HST) in terms of economic potential.
The results of the method are not intended to assess the economics of hypersonic flight, nor to assess the design or operational characteristics of aircraft.

In general, the method proposed by NASA is applicable to all passenger or cargo aircraft capable of operating a cruise at hypersonic speed and with horizontal take-off and landing capability, using airbreathing engines for propulsion.

Within these definition limits of the basis of calculations the method has good flexibility to take into account broad mission and design variables. For this, the method can still be used outside of these parameters being careful to correctly assess the impact of the technological parameters.

The methodology is divided into 5 phases.

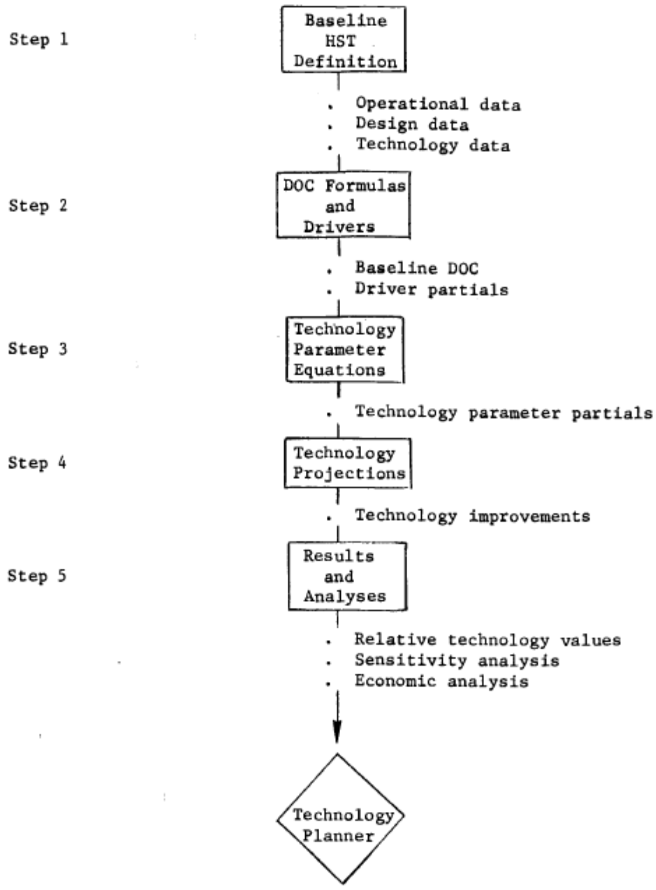


Figure 45 - Flowchart of NASA Cost estimation methodology [2]

The first phase begins with the baseline HST definition. This baseline can be associated with any mission system or configuration for which you want to determine the value of the costs related to potential technological improvements. This step requires that the benchmark on which to assess these changes in costs is obtained from independent studies or data sources. The output of this first step is the vehicle and mission data, specifically needed for the next steps of the methodology.

The second step of the method is to use formulae for the calculation of Direct Operating Costs (DOC) for the baseline. These formulas comply with the proposed conventions of the Air Transport Association of America (ATA), but are modified to adapt them to the study of hypersonic aircraft.

In this step therefore they come identified the so-called DOC "Driver"; that is all those parameters of the formulas Doc that have a significant impact on the last ones and that are directly referable to hypersonic airplanes. As already described at the end of Chapter 1, the DOC formulae are derived from the formulae proposed by the ATA method "Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Planes" in the 1967 version [1]. In this ATA review, I develop a cost estimation model suitable for aircraft operating up to a maximum cruising mach of 5, based on cost data provided by airlines and manufacturers.

NASA [2] then extended these equations to hypersonic aircraft using extrapolation and the introduction of new factors.

The third step of the method is to calculate the impact that the variation of the technological parameters (TP) has on the DOC Driver. By definition, TP are parameters that are lower in level to the Drivers and that are referable to specific areas of hypersonic research and are specified in the baseline obtained from the first phase.
The next fourth phase involves the projection of technological advances in addition to the state-of-the-art embedded in the basic HST. Projections are made at the level of technological parameters seen within phase three. Each of these projections is assessed by the relevant specialist of that particular technology. These then become the main inputs of the next phase.
The fifth and final phase, integrates at this point the previous data to produce estimates of the potential savings of DOC offered by the advances of hypersonic technologies. Therefore, the relative saving of DOC by technological sector is the main product of the methodology.
To qualify the product, step five also includes a sensitivity analysis and an economic analysis.
The sensitivity analysis examines the impact of uncertainties on economic values related to the technologies used. The uncertainties, therefore, apply to the semi-empirical constants contained in the DOC formulae and to the expected technological improvements.
If sensitivity and economic analyses qualify the results by validating them, the product is approved and is then passed on to those responsible for technological planning.

4.2. Baseline HST NASA

The relative economic payoff of technology improvements is dependent upon the requirements and characteristics of the reference HST baseline (e.g. its mission, configuration, design features and technology state-of-the-art).
The fundamental purpose of the module "Baseline HST definition" is to organize the relevant data in a way that is appropriate to be exploited within the remaining phases of the general method such as within the DOC technology modules.
In carrying out this purpose, information from previous studies is used at this stage. The next process then responds to the basic rules and constraints that are part of the initial input of this phase.
The basic definition method is divided into two main parts:

- Information Processing - with the aim of forming a complete and coherent information package going to acquire and filter data for HST to be used for the preparation of the next documentation useful for the next steps.

- Documentation - or prepare the baseline definitions output. The documentation will contain the data of the aircraft related to mission, operation, performance, design, weights and technological data. These data will be present both in tabulated quantitative form (useful for the successive DOC and Technological parameters equations) that in descriptive form to provide both an adequate understanding of the HST baseline and its technology and to ensure a certain flexibility in the preparation of information content to accommodate special areas of technical interest.

As previously mentioned, the HST baseline definition applies specifically to hypersonic aircraft that use airbreathing engines that can take off and land horizontally.
Within these limits, however, the baseline definition method has the ability to adapt to certain mission and design variables, as summarised in the following table:

Variable Category	Major Alternatives Accommodated
Payload	Cargo, passenger or combination
Cruise Mach number	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 1 – Design variables in NASA methodology [2]

- Variations in payload type have minimal effect on baseline development because the density of an airplane passenger compartment is comparable with the density required to accommodate most potential cargos. In the case of a liquid hydrogen-fuelled airplane, where the fuel density is similar to cargo or
- passenger compartment densities, payload weight variations maybe traded for fuel, with subsequent range changes.
- The parameters and relationships in this method are generally applicable to the hypersonic Mach number of 5 to 12. Mach beyond this interval should not be treated without a preliminary assessment of suitability.
- Although the model for the definition of the HST design baseline are highly dependent on the type of fuel, the basic methodology is not. This leads to also consider different types of fuel.
- The definition of structures is expressed in fractions of weight and values of parameters associated with the Technology. (e.g. parameters of housing, method for cooling structures, types of tanks whether integral or not).
- The method is able to adapt to large variations in aerodynamic configuration (L/D ratio)
- Basically, this method is formulated to describe two types of propulsion systems, one accelerator/descent type and the other accelerator/cruise type. So, it is able to adapt to turbojet engine systems - Ramjet or single Ramjet-scramjet engines.

It is therefore necessary to refer to two types of input data, in order to be able to develop this first phase.
The first type of data related to requirements and ground rules with the purpose of:
(1) identify the HST project covered by the baseline definition;
(2) identify the reference documentation from which the required data are to be extracted;
(3) identify descriptive data related to technological particulars.
The other type of data, on the other hand, is related to the actual data of the HST (associated technological parameters and other qualification characteristics).
The types of input data needed for the preparation of the output modules useful for the following phases include data related to mission, performance, operations, aerodynamics, propulsion, design, structures, weights and related technologies.

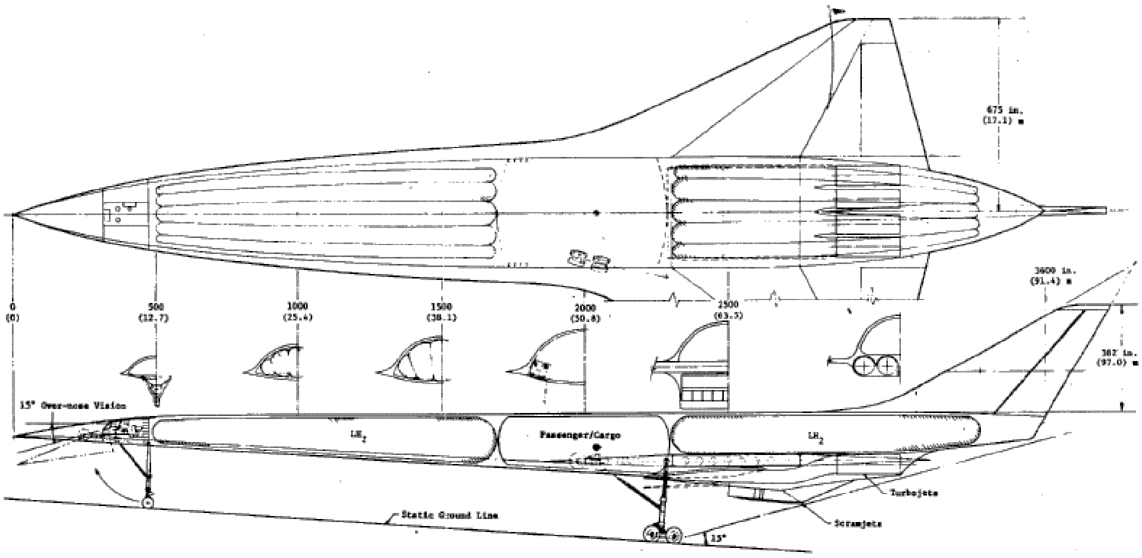


Figure 46 – NASA HST concept [2]

A demonstrative example of this phase of the method of esteem of the costs used a airplane from cargo with a Mach of cruise pairs to six and with an operating capacity of 7400 km. The profile of the mission for HST sees the cruise to be realized to an altitude between the 27600 m and the 28800 m and a mission duration of about 2 hours.
Aerodynamic performance is reported in terms of aerodynamic efficiency L/D, with a reference value of 4,6 (the most conservative of that obtained in the wind tunnel test). Other operational characteristics required by the method and presented are:
Block time:2.25 hr
Average utilization: 3000 block hr/yr
Deplorable life: 10 yr
Hours of use during operational life: 30000 hr
No-use hours during operational life: 576000 hr
Flight hours over the operational lifecycle:26700 hr
Flight cycles during operational life: 13350
The fuel used is liquid hydrogen, with tanks located at the front and rear of the fuselage for considerations related to the weight and centre of gravity of the fuselage,

as well as for reasons of stability and balance control. This includes the positioning of the loading space. The shape of the fuselage blended wing-body with a single vertical rearing that guarantees a reduced aerodynamic resistance and a surface of continuous pre-compression for the engines. The material of the structure is 7075-T6 aluminium alloy cooled to an average temperature of 367k through the use of a water-glycol-based refrigerant fluid and special heat exchangers.
A combo engine, consisting of 4 turbojets for subsonic speeds and a series of dual-combustion Ramjets, is examined as a propulsion system (subsonic combustion during the transition from transonic velocity to supersonic, and supersonic combustion to address hypersonic phases).

4.3. DOC Formula and Drivers HST NASA

The equations for calculating direct operating cost for the HST aircraft as a function of Driver Parameters. The change in the DOC would result from improvements in the values of the Driver Parameters. By definition, the Driver
Parameters are parameters appearing in the DOC formulas which are directly relatable to hypersonic technology.
The DOC values are expressed in the form of cents per ton-mile. The changes in the DOC which result from improvements in the Drivers are calculated using equations called Driver. These equations and are expressed in the ratio (ΔDOC/DOC)/(ΔDriver/Driver) called "Driver Partials".
Variations in the values of the Driver Partials, (ΔDOC/DOC)/(ΔDriver/Driver), which would result from uncertainties in parameters other than Drivers which are treated as constants in the DOC formulas are reported in a sensitivity analysis, included in this phase. The "sensitivity parameters" include operational and cost factors which are a matter of judgment or independent estimate such as aircraft utilization, load factor, or the purchase price of fuel.
The input data for this phase consist of the aircraft and mission parameters provided by the output of phase 1 (Baseline HST Definition).

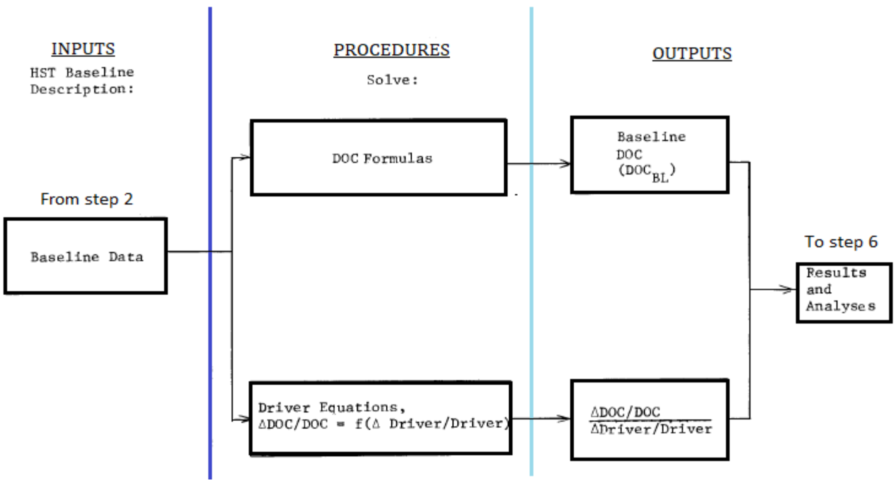


Figure 47 – Main steps diagram in NASA methodology [2]

Symbol	Units	Parameter
Driver Parameters		
L/D	-	Cruise lift-drag ratio
sfc	kg/N-hr	Specific fuel consumption
W_{AF}/W_{GTO}	-	Airframe weight fraction
$(W/T)_{TJ}$	-	Turbojet specific weight
$(W_{RJ})/(A_C C_{TRJ})$	kg/m²	Ramjet sizing parameter
Other Aircraft Parameters		
A_C	m²	Total cowl inlet area, ramjet engines
N_{TJ}	-	Number of turbojet engines per aircraft
N_{RJ}	-	Number of ramjet engine modules per aircraft
T_{TJ}	N	Turbojet thrust (SL static) per engine
$(T/W)_{GTO}$	-	Maximum thrust to weight ratio at take-off
W_{AV}/W_{GTO}	-	Avionics equipment weight fraction
W_{FT}/W_{GTO}	-	Fuel weight fraction
W_{GTO}	kg	Gross take-off weight
W_{PL}/W_{GTO}	-	Payload weight fraction
W_{RJ}/W_{GTO}	-	Installed ramjet engines weight fraction
W_{TJ}/W_{GTO}	-	Installed turbojet engine and duct weight fraction
Mission Parameters		
K_D	-	Descent fuel fraction
K_R	-	Reserve fuel fraction
K_CL	-	Climb fuel fraction
Mission Parameters	-	Cruise Mach no.
R_T	km	Operational range
t_F	hr	Time of flight
V_B/V_CR	-	Ratio, block velocity to cruise velocity

Table 2 – NASA baseline required parameters [2]

The input data are processed for:

1) Determine the baseline DOC value for each of the DOC elements and for the DOC total using the DOC formulas.
2) Determine the Driver Partial for each Driver Parameter and DOC element using the Driver Equations.

A DOC formula exists for each DOC element like fuel, crew, insurance, etc. These are then summed to give DOC Total. The operational constants and cost factors not given in the baseline HST definition, but required to solve the DOC equations are provided by external data.

The input and output values of all cost values in the DOC formulas are in dollars, so that the calculated DOC values are in $\$_{1973}$ per ton-mile. The formulas and the inputs are expressed with coefficients in SI units.

The DOC formulas are based on the formulas developed by the Air Transport Association of America (ATA), entitled Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Planes.

The last revision, based on commercial airlines' costs and experience, covers turboprop and turbojet subsonic aircraft and supersonic aircraft of the SST class. In the present analysis the ATA formula [1] for the subsonic and supersonic aircraft have been examined and extrapolations have been made or factors introduced when required to extend the supersonic aircraft formulas to the HST case.
The quantity of fuel to be used by the HST has been developed separately with direct application to the HST aircraft configuration.

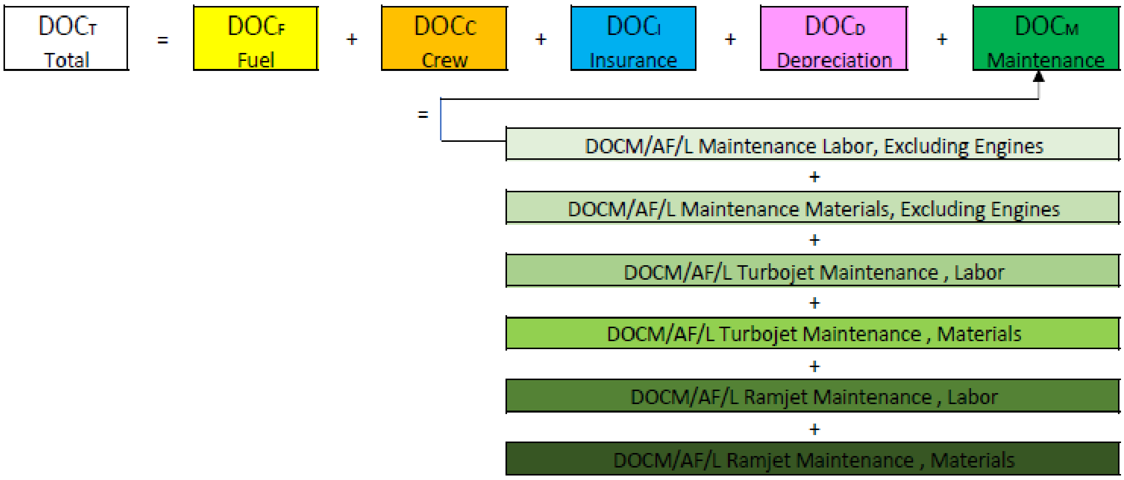


Figure 48 - Direct Operating Cost breakdown in NASA methodology [2]

DOC Fuel:

The cost of fuel per flight is expressed simply by the ATA [1] as the unit cost of fuel times the quantity used.

$$DOC_F = \frac{1460\ C_f\left(\frac{W_{f_t}}{W_{GTO}}\right)(1-K_R)}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right)R_T}$$

Where:

C_F = cost of fuel per unit weight, [$/kg];

W_{fT}/W_{GTO} = fuel weight fraction;

K_R = reserve fuel fraction (usually defined by legislation); it is a percentage of total fuel weight and it should be less than one;

R_t = operational range, [km];

W_{PL}/W_{GTO} = Payload weight fraction;

LF = average load factor [%/100]; (for HST is suggest 0.6 unless specified).

The load factor is the ratio of the average payload carried to the maximum payload which the aircraft is capable of carrying in normal operation. In 1971, the industry average was 44%. Cargo planes in regular operation run higher than passenger planes. Therefore, a value of 60% has been used for the HST calculation.
For Cost of fuel Cf, a typical value during the 1973 for liquid hydrogen delivered to a user site is 20 cents per pound (44 cents per kg).

DOC Crew:

Crew costs include crew salary, fringe benefits, training programs and travel expense. The large subsonic jets have a crew of three which was planned for the SST and is the assumed number for the HST. Stewardess' costs associated with passenger airlines are classified as a "Passenger Service Cost" which is an indirect operating cost.

$$DOC_C = \frac{\left(\frac{320}{W_{GTO}}\right)}{0.725\ (LF)\ \left(\frac{W_{PL}}{W_{GTO}}\right) M \left(\frac{V_B}{V_{CR}}\right)}$$

Where:

W_{PL} = payload weight, [kg];

M =cruise Mach number;

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

DOC Insurance:

Insurance cost covers insurance of the aircraft itself and is calculated simply as an annual rate time the acquisition cost of the aircraft. The insurance rate it is difficult to estimate. In general, this term is linked to external factors and related to the policies taken out by insurance companies and airlines that can vary profoundly also depending on the country in which it is stipulated and the current legislation. In a first approximation, it can be expressed as a percentage of the total vehicle cost (typically 5% of the original acquisition cost) however, during the life of vehicle, this coefficient decreases quickly (to 2% after 4 year).

$$Annual\ insurance\ cost = (IR)\ (C_{HST})$$

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

Where:

IR = annual insurance rate, [%/100] (for HST is suggest 0.2 unless specified);

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

U = aircraft utilization, [block hrs/yr.]

Aircraft utilization is the average block hours of use of the aircraft in a year. Typical utilization for industry varies from about 3000 hours to 4500 hours during normal times depending on the aircraft and air lines involved. 3000 hours, at the low end of the scale, was selected for the HST because of its high speed and short flight time.

DOC Depreciation:

Depreciation cost is an expense provided to recover the original cost of the aircraft, plus the initial stock of spare parts, over an assigned depreciation life of the aircraft (subsequent purchase of spares to replace spares used from the initial stock are a maintenance expense).
The depreciation life depends on the policy of the airline and on the technologies on board.15 years is a typical value for subsonic commercial aircraft. For HST this value is shortened to 10 years.

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

Where:

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

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

L_d= depreciation life of aircraft [yr].

Acquisition costs for the total aircraft C_{HST} and certain of its elements are required for use in the DOC formulas. These costs may be developed independently, by any method, or they may be estimated using the following estimating relationships which have been developed for the baseline HST.

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

Where:

C_{HST}= total cost of HST aircraft [$];

C_{AF} = cost of airplane less engine and avionics [$];

C_{RJ} = cost of ramjet engine set per aircraft [$];

C_{TJ} = cost of turbojet engine set per aircraft [$];

C_{AV} = cost of avionics [$];

W_{GTO}= gross take-off weight [kg].

$$\frac{C_{AF}}{W_{GTO}} = \frac{855\, {W_{AF}}^{0.68}\, M^2}{W_{GTO}} \quad ; \quad \frac{C_{TJ}}{W_{GTO}} = 6300\, {N_{TJ}}^{-0.15}\, {T_{TJ}}^{-0.33} \left(\frac{T}{W}\right)_{GTO} ;$$

$$\frac{C_{RJ}}{W_{GTO}} = \frac{33900\,(A_C)^{0.9}\, M^2}{W_{GTO}} \quad ; \quad \frac{C_{AV}}{W_{GTO}} = 2760 \frac{W_{AV}}{W_{GTO}}$$

DOC Maintenance:

The maintenance formulas are based on cost estimating relationships developed from industry data on airline maintenance costs. In the case of the airframe and subsystems, other than engines, the ATA [1] expressions include velocity, weight, and cost terms which make them applicable to both subsonic and supersonic planes of the SST class. These equations have been considered applicable for the Extrapolation to the HST case. The ATA formula [1] has been simplified where it was determined that the simplification could be introduced without significantly changing the maintenance estimates.
The ATA formulas [1] divide maintenance costs into four categories, separating the engines and the remainder of the aircraft and separating each of these into labor and materials. In each category, the ATA introduces terms reflecting maintenance actions related to flight cycles and maintenance actions related to flight hours. The former covers items such as the landing gear which is used once each flight or inspections which occur on a per-flight basis. The latter covers wear and tear and periodic maintenance actions which occur on a per-flight-hour basis.
In the case of engines, the ATA introduced larger coefficients in the estimating relationships for the supersonic (SST) engines than for the subsonic engines. This in effect amounted to the equivalent of estimating maintenance costs for supersonic turbojet (SST) engines by taking a ratio to the costs for subsonic turbojets of comparable size. The value of this ratio for SST supersonic turbojets to subsonic turbojets from the ATA cost relationships [1] is equivalent to approximately 1.7 to 1.

$$DOC_M = DOC_{M/AF/L} + DOC_{M/AF/M} + DOC_{M/TJ/L} + DOC_{M/TJ/M} + DOC_{M/RJ/L} + DOC_{M/RJ/M}$$

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.

DOC airframe and subsystems maintenance labor:

The formula was a reasonable extension of ATA [1] expression (applicable to both subsonic planes and to the SST) to apply it to the HST where the term M = 6 yields maintenance costs of about 2.4 to 1 over subsonic airplane.

$$DOC_{\mathrm{M/AF/L}} = \frac{(3.22 + 1.93\, t_F)\left[0.05 * \left(\frac{W_{AF}}{W_{GTO}} + \frac{W_{AV}}{W_{GTO}}\right) + \left(\frac{6}{W_{GTO}} - \frac{630}{\left(\frac{W_{AF} + W_{AV}}{10^3} + 120\right) W_{GTO}}\right)\right] M^{\frac{1}{2}}\, r_L}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

Where:

t_F = time of flight [hr];

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

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

r_L = average labor rate for all personnel involved in maintenance [$].

For all maintenance personnel, the ATA [1] gives $4.00 as the input value for average labor rate in its formula during 1967. However, this value, has been increased to $5.30 in 1973 by allowing a 6-percent annual increase in 5 years.

DOC airframe and subsystems maintenance materials:

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

DOC Turbojet engine maintenance labor:

$$DOC_{\mathrm{M/TJ/L}} = \frac{\left(\frac{T}{W}\right)_{GTO} (1 + 0.3\, t_F)\left(\frac{8.6}{T_{TJ}/10^3} + 0.087\right) r_L\, K_{LTJ}}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

Where:

$(T/W)_{GTO}$ = thrust to weight ratio at take-off;

T_{TJ} = thrust of turbojet engines per engine (sea static level) [N];

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

DOC Turbojet engine maintenance material:

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

Where:

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

The ATA formulas [1] on which the DOC formulas are based covered supersonic (SST) as well as subsonic turbojets and utilized coefficients in their supersonic and subsonic formulas which gave an equivalent value of K_{LTJ} and K_{MTJ} of approximately 1.7 to 1. A value of 2.0 to 1 has been used in the demonstration calculations for the HST because the HST turbojets are estimated to have higher maintenance requirements per hour of operation than the SST turbojets.

DOC Ramjet engine maintenance labor:

Scramjet maintenance labor is estimated in a manner similar to that for the HST turbojets by introducing ratios for ramjet maintenance to subsonic turbojet maintenance into the ATA expressions [1] for subsonic turbojet maintenance.

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

Where:

L/D = cruise lift to drag ratio

N_{RJ} = number of ramjet modules per aircraft

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

DOC Ramjet engine maintenance material:

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

Where:

K_{MTJ} = ratio, maintenance material for Ramjet engines to present subsonic turbojet engines.

For scramjet engines, factors of KMR J = 3 and KLR J = 2 have been used in the demonstration calculations for materials and labor, respectively. The scramjet will operate at much higher temperature, (3000 K) compared with turbojets (1400 K). Although they have no rotating machinery, they will have regenerative cooling. A value of 2 instead of 3 was selected for the labor factor to reflect a labor requirement reduced by one-third per maintenance action because of the essentially simple construction of the scramjet versus the turbojet engine.

Drive definition:

	Baseline DOC Values [$ Per Ton-Mile]	Driver Partials for Driver Parameters				
		$\frac{W_{AF}}{W_{GTO}}$	$\left(\frac{W}{T}\right)_{Tj}$	$\frac{W_{RJ}}{A_c/C_{TRJ}}$	L/D	sfc
DOC_F Driver Partial Driver Partial x DOC_F						
DOC_C Driver Partial Driver Partial x DOC_C						
DOC_F Driver Partial Driver Partial x DOC_F						
DOC_I Driver Partial Driver Partial x DOC_I						
DOC_D Driver Partial Driver Partial x DOC_D						
$DOC_{M/AF/L}$ Driver Partial Driver Partial x $DOC_{M/AF/L}$						
$DOC_{M/AF/M}$ Driver Partial Driver Partial x $DOC_{M/AF/M}$						
$DOC_{M/TJ/L}$ Driver Partial Driver Partial x $DOC_{M/TJ/L}$						
$DOC_{M/TJ/M}$ Driver Partial Driver Partial x $DOC_{M/TJ/M}$						
$DOC_{M/RJ/L}$ Driver Partial Driver Partial x $DOC_{M/RJ/L}$						
$DOC_{M/RJ/M}$ Driver Partial Driver Partial x $DOC_{M/RJ/M}$						
TOTAL						
DOC_{BL} $\sum$(**Driver Partial** $\times$ **DOC$_i$**)						
Driver Partial$_{total}$ = $\frac{(\sum(Driver\ Partial \times DOC_i)}{DOC_{BL}}$						

Table 3 – Driver Partial Table in NASA methodology [2]

Driver parameters have been defined as parameters which enter into the calculation of DOC and significantly impact its value and which are directly relatable to hypersonic technology. The following terms have been defined as Driver Parameters:

1. W_{AF} / W_{GTO} = aircraft weight fraction
2. $(W / T)_{TJ}$ = Turbojet propulsion specific weight
3. $W_{RJ} / A_C C_{TRJ}$ = Ramjet sizing parameter
4. L / D = Lift to drag ratio
5. sfc = Specific fuel consumption

In most of the DOC equations, the Driver Parameters are contained in the two terms W_{fT} / W_{GTO} (fuel fraction) and W_{PL}/W_{GTO} (payload fraction) expressed by the formulas:

$$W_{f_T}/W_{GTO} = \frac{1 - \exp\left\{9 \times 10^3 \frac{R_T \ sfc}{\frac{L}{D} \ M} \left(1 - 0.75 \frac{W_{f_{CL}}}{W_{f_T}}\right)\right\}}{\frac{W_{f_{CL}}}{W_{f_T}} - [1 - (K_D + K_R)] \exp\left\{9 \times 10^3 \frac{R_T \ sfc}{\frac{L}{D} \ M} \left(1 - 0.75 \frac{W_{f_{CL}}}{W_{f_T}}\right)\right\}}$$

$$\frac{W_{PL}}{W_{GTO}} = 1 - \frac{W_{AF}}{W_{GTO}} - \frac{W_{AV}}{W_{GTO}} - \frac{W_{f_T}}{W_{GTO}} - \left(\frac{W}{T}\right)_{TJ} \left(\frac{W}{T}\right)_{GTO} - \left(\frac{W_{RJ}/A_C}{C_{TRJ}}\right) \frac{C_L}{(L/D) \ (W/S)_{GTO}}$$

The five Driver Parameters given above are used along with the basic DOC equations to develop the "Driver Partials" trough the "Driver equations". The "Driver Partials" are expressed in the form (ΔDOC / DOC) / (ΔDriver / Driver) for each element of DOC and for each driver.

4.4. Technological parameters and technology projection

In the last two phases of the NASA method [2], the effects of technological parameters and projections on driver parameters and consequently on costs are studied.
The fourth module presents the procedures and equations necessary to determine the effects of the changes some selected Technological Parameters on the designated Driver Parameters.
To determine the effects of the changes on the driver parameters it is necessary to first define the relationship between them and the technological parameters. These operations are conducted both analytically through explicit equations and empirically through the use of graphs.
For example, going to consider the driver parameter WAF/WGTO (aircraft weight fraction) this is divided into a number of elements characterizing the technological parameters that have an impact on this driver (for example, the weight of the fuselage and the weight of the wing contribute to most of the weight of the cell, so they also have a great impact on this driver parameter).
It is necessary that the elements selected as technological parameters are representative of the design properties and factors to allow the cost study to take

place with maximum flexibility in determining the technological effects on each of the drivers' parameters.
Subsequently, it is necessary to make estimates of potential technological improvements that could have an impact on the operating cost.
These estimates of technological improvements, derived from an appropriately documented evaluation process, must be carried out by specialists in the various technological areas concerned (aerodynamics, propulsion, cell design and materials).
The logic behind this process will include considerations on the integrated technology in the reference aircraft, historical trends, fundamental physical limits and considerations on future technological developments.
In order to ensure consistency across the whole range of technological projections,
A "Technological Scenario" will be provided which will present a framework of perspectives and conditions within which these new technological developments can be expected to be introduced.
Finally, the method involves collecting the results and verifying the results obtained in order to ensure proper technological planning (principal product of the subject methodology).

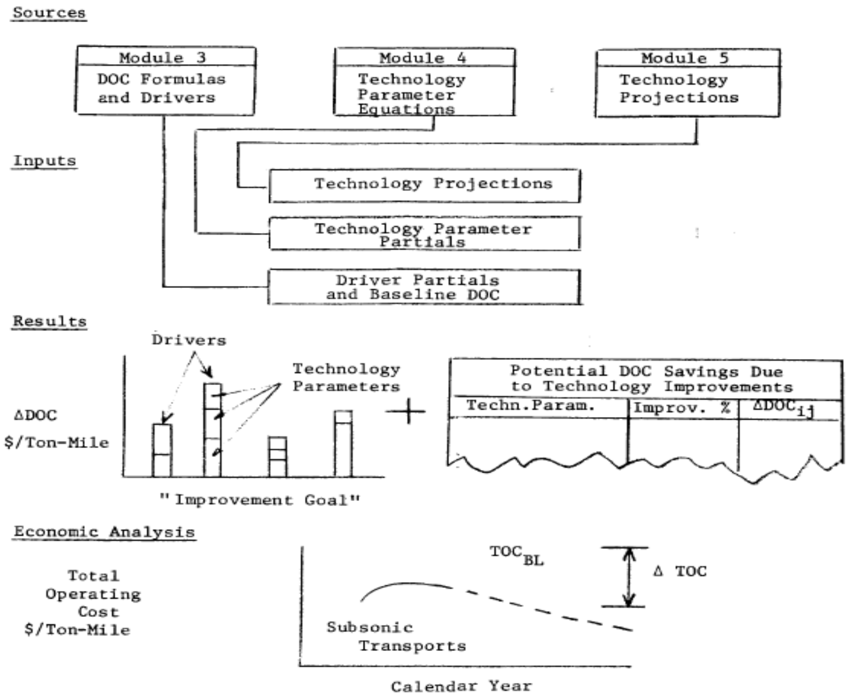


Figure 49 – NASA methodology result and economic Analysis illustration [2]

$$\Delta DOC_{ij} = (DOC)_{BL} \times \left(\frac{\Delta DOC/DOC}{\Delta Dr/Dr}\right)_J \times \left(\frac{\Delta Dr/Dr}{\Delta Tp/Tp}\right)_{iJ} \times (\Delta Tp/Tp)_i$$

The abscissa for each of the drivers is calculated here in and represents a set of achievable "goals" for the constituent technologies. The ordinate represents the potential economic gain realized by achieving the goals.

5. Analysis and update of DOC calculation model

In this chapter, there is a deeper analysis of the NASA mathematical relationships of the reference [2], to correct and update equations set allowing the evaluation of the impact of technologies on direct operating costs.
An important part is the deeper analysis of each cost driver of the NASA equation [2] and in particular the effect of the cost drivers of those formulas on the DOCs.
An analysis is then performed on the factors that can modify the values obtained by the relative CERs
A detailed analysis of the equations proposed by the NASA methodology [2] will therefore be carried out to be able to understand the impact that the various cost drivers have on costs.
From a technological point is interesting investigate on the fuel and maintenance equations.
In case of liquid hydrogen supersonic aircraft, there are not any airplanes on service, that can be used as references for the cost 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. In this case, the possible solution is to compare the results deriving from different estimation models.
In the NASA report [2], there are some relationships for evaluating the acquisition cost of the aircraft and some of its subsystems. Through to NASA method [2] is possible evaluate the acquisition cost. The acquisition cost is directly linked to performance and on the typical features of the aircraft.
Analysing the impact factors on DOC, in the case of the direct operating cost of fuel, the cost per unit of weight of fuel is the most important factor for this CERs. In the analysed case, Green Concorde [7] use liquid hydrogen to reach their purpose. However, in 2021, the amount of liquid hydrogen as a fuel is not enough to satisfy an increase of demand deriving from the aerospace sector. In the future the production plants should increase their production capacities to satisfy that market request.
The market price of liquid hydrogen depends on different factors:
-production technique;
-production rate;
-production country

For the cost of maintenance, as a show in NASA method [2], this considers the contribution of the different engines and the airframe. For each of them is evaluated two costs items:
-maintenance labor;
-maintenance material.

The labor item includes the hourly salary of maintenance workers (linked to level of specialization, years of experience, various national minimum wage policies and economic policies of airlines). The material cost depends to the acquisition cost of the aircraft, of the engine and the costs of the spare parts.
From historical references, it is possible to assess how the maintenance costs of supersonic aircraft are higher than those incurred by subsonic aircraft given their

greater level of complexity. This obviously leads to taking into account in the formulas of the corrective coefficients that take into account this aspect. In addition, current data on use of liquid hydrogen systems in industrial applications have shown that these systems are also subject to a high maintenance rate with a request for replacement of components. The maintenance equations depend on many cost drivers, because the maintenance is an aspect that concerns all the parts of the vehicle (not only engine and airframe, but any other on bord system). It is difficult to identify which parameter can have a great impact on the cost of maintenance in a preliminary phase of the work.

Market trends and economic policies of companies strongly modify the crew, insurance and depreciations cost.

As report in the chapter 2, the cost of the crew depends not only on the salary of crew but also on the benefits for the pilots and cabin crew. The hourly crew salary is defined on the base of different factor such as aircraft features (maximum take-off weight, payload, cruise speed, range). Generally, salary tends to increase as the performance or weight of the aircraft increases. Other factors are: mission profile, experience gained over the years by the staff. Moreover, each airline can define its own rules or the salary.

Regarding the cost of insurance, this is difficult to estimate at this stage of project. This essentially covers the risk of damage or loss of the aircraft and damage to passengers or third parties in the event of an accident.

In general, it is the airline company chooses the type of insurance policy.

Insurance companies tend to vary their fee according to nature (i.e., geographical areas of flights) and the safety levels offered by airlines during their missions, not that by the failure rate of the vehicle. It is possible to observe a relationship between the cost of an insurance policy and the rate of loss of the vehicle or "actuarial losses", in fact, as the accident rate of a vehicle increases, an increase in the cost of insurance is observed.

Typical premiums for insurance vary between 1 and 3% of the cost of the aircraft. At this point, if you want to estimate the value of the cost related to insurance, is possible use (at this stage of project) as typical values 2% of the vehicle cost.

For the depreciation cost it is important to assess the operational useful life that the airline decides to allocate to the aircraft before decommissioning it. Every company can choose the final residual value to attribute to the airplane or to the parts of which it is composed before the decommissioning. Therefore, if the residual value is not zero is possible for the airline company resell them. IATA [] suggested a depreciation life between fifteen and twenty years without residual value. For the supersonic aircraft, the useful life is comparable as subsonic aircraft, however, considering the supersonic reference aircraft that have actually operated, their operational life has been about thirty years.

5.1. Fuel cost driver factors

As a NASA method report [2], the CERs of fuel cost is:

$$DOC_F = \frac{1460\ C_f \left(\frac{W_{ft}}{W_{GTO}}\right)(1 - K_R)}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

Where:

C_F = cost of fuel per unit weight, [\$/kg];

W_{ft}/W_{GTO} = fuel weight fraction;

K_R = reserve fuel fraction (usually defined by legislation); it is a percentage of total fuel weight and it should be less than one;

R_t = operational range, [km];

W_{PL}/W_{GTO} = Payload weight fraction;

LF = average load factor [%/100]; (in 2019 IATA estimated a worldwide average load factor of 85% for subsonic transport, but in 2020 due to pandemic crisis, this value is fell of 25% reach a minimum value of 60%. Now, the values are coming back over 70% as a show in the table below [52]).

JULY 2021 (% VS JULY 2019)	WORLD SHARE[1]	RPK	ASK	PLF (%-PT)[2]	PLF (LEVEL)[3]
Total Market	**100.0%**	**-53.1%**	**-45.2%**	**-12.4%**	**73.1%**
Asia Pacific	38.6%	-62.7%	-54.1%	-15.4%	67.5%
Europe	23.7%	-56.5%	-46.5%	-16.5%	72.5%
Latin America	5.7%	-44.5%	-40.5%	-5.8%	79.3%
Middle East	7.4%	-73.2%	-57.5%	-30.0%	51.3%
North America	22.7%	-28.5%	-24.7%	-4.5%	84.1%

1) % of industry RPKs in 2020 2) Change in load factor vs. the same month in 2019 3) Load Factor Level

Table 4- Load factor level before and after COVID-19 pandemic [52]

As previously indicated, the load factor is the ratio of the average payload carried to the maximum payload which the aircraft is capable of carrying in normal operation. Therefore, a value of 70% has been used for the SST calculation (60% for HSP).
All the elements are expressed using units from the International System.
This equation is derived from estimating DOCs published by ATA in December of 1967 [1].
That equation is applicable using all type of fuel because the fuel features are expressed only by the cost of fuel for unit of weight Cf.

In addition, it is useful to report here also other drivers (outside of this analysis) but impacting on the direct operating cost of fuel mainly related to supersonic aircraft specifications such as:

- Structure (Fuselage configuration and type modify influence cl and cd and consequently fuel quantity e maximum take-off weight)
- Materials (new material adopted influence maximum take-off weight)
- Systems (system weight influence maximum take-off weight)
- Propulsion system (strategy influence fuel quantity and maximum take-off weight)
- Legislation (legislation influence fuel quantity trough fuel reserve)
- The mission (fuel quantity).

5.1.1. Fuel cost

Analysing the various terms that make up the previous report, it is possible to observe that the price of Cf fuel plays a key role in the amount of costs.
As already mentioned above, this term depends strictly on the type of fuel used as fuel (In the case under consideration we will focus on the cost related to liquid hydrogen).

Given the particularity of this type of fuel it is necessary to make some considerations at a technological level to evaluate what may be the other aspects on which the use of this fuel impacts. In fact, its use substantially modifies what concerns the fuel supply system and in part also the propulsion system, the geometry and configuration of the structure (including the materials to be used), the mission and ground operations.
Even if hydrogen is the most abundant element in the universe, on Earth, it is mostly found back in one or another molecular form, e.g., water and hydrocarbons, and therefore, it must be extracted for its various uses. Hydrogen's very high energy content per unit mass makes it very appealing and competitive in aerospace, but in the other hand it has a low volumetric energy density which required important choices at the level of design and configuration of the aircraft, moreover hydrogen as propellant can allow a complete decarbonization of the flight. These positive combustion characteristics make hydrogen the ideal fuel for gas turbine engines. Liquid hydrogen allows a very stable combustion over an equally wide range of operating conditions. The main products of its combustion are water vapor, while CO, CO_2, unburned hydrocarbons and particulates are eliminated, NOx are still formed (for any kind of fuel, it depends by flame temperature inside combustor zone). The exploitation of hydrogen as propellant might cause material embrittlement, posing serious constrain on material selection. In addition, the cryogenic storage is the only viable option and this poses some challenges to the designers.
The presence of cryogenic fuel on board can be an important benefit for thermal management.

As show in [9], for evaluation of LH2 price is very important consider the production rate, the production techniques and the production country.

Properties	Advantages	Disadvantages
High heat of combustion	Reduced fuel weight Reduced gross weight Reduced SFC	More stringent safety requirements
Low Molecular weight	High specific heat Higher cooling capabilities	Materials more prone to (hydrogen) embrittlement Innovative material shall be developed
Low density	Lower wing loading	Increased tank volume Larger external wetted area resulting in larger viscous drag
Cryogenic	Lighter tank and fuel system Lowering of thermal management system mass Larger on-board cooling capability Lighter tank and fuel system Enables lowering the thermal management system mass. Larger cooling on-board capability	Specific light weight cryogenic insulation system required e.g. avoiding cryo pumping New and expensive materials might be required

Figure 50 - Effects of LH2 as propellant on aircraft design and performance [8]

In detail for production technique, depending on sources and feedstocks used and, on the technologies, hydrogen is mainly produced using fossil fuels with significant carbon emissions (“grey” hydrogen) or through a proper Carbon Capture Utilization and Storage technologies (“blue” hydrogen) for which the carbon emissions are captured and stored, or reused. The cleanest of all is “green” hydrogen, which is generated by renewable energy sources without producing carbon emissions (in the first place).

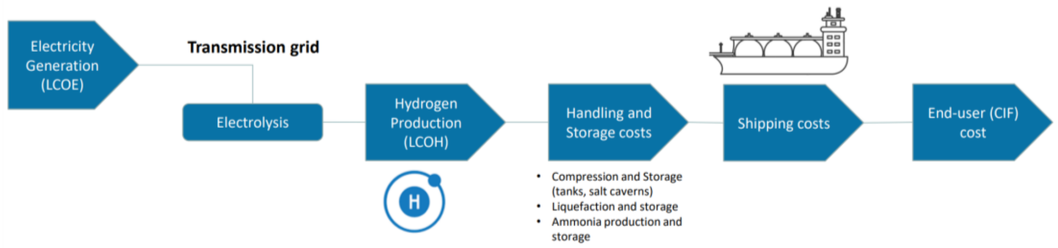


Figure 51 – Green Hydrogen supply chain [11]

The historical data collected by IEA [58] regarding overall production of H2 show current annual production is greater than 77 million tons with an expected increase of about 20% by 2030 and of 60% by 2050.

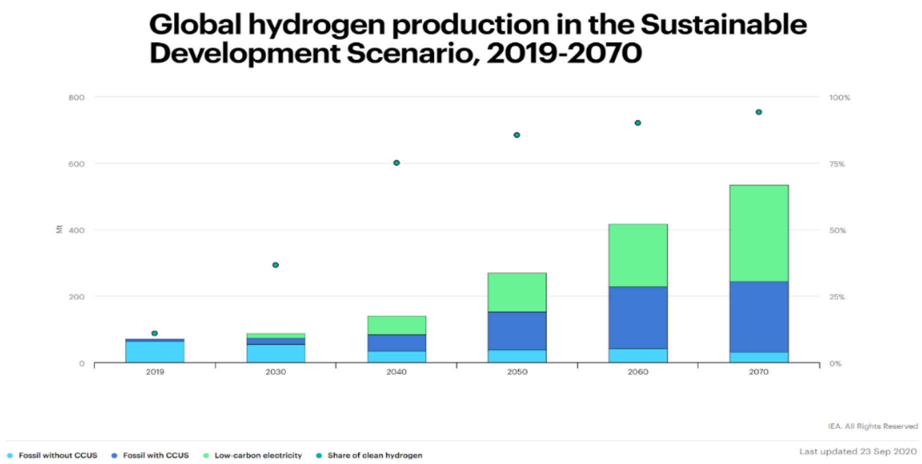


Figure 52 - Global hydrogen production derived from [58]

Hydrogen production technologies might be grouped into two different families:
– Hydrogen separation from hydrocarbons
– Hydrogen extraction from water
– Hydrogen extraction from nuclear reactors via thermochemical processes
Considering the production of hydrogen from water, different energy sources need to be investigated.
Though electrical power can be directly used to run electrolysers from a wide range of sources:

- fossil fuels
- nuclear plant
- wind energy
- solar energy
- biomass

Looking specifically at electrolysis technologies, two main technologies are currently used for hydrogen mass production: Alkaline and Proton Exchange Membrane (PEM).
Compared the two technologies highlighting main advantages and disadvantages [56].

Technology	Advantages	Disadvantages
Alkaline Electrolysis	Technology: oldest and well established Cost: cheapest and effective Catalyst type: noble Durability: long term Stacks: MW range Efficiency: 70% Commercialized	Current density: low Degree of purity: low (crossover of gases) Electrolyte: liquid and corrosive Dynamics: low dynamic operation Load range: low for partial load Pressure: low operational pressure
PEM Electrolysis	Current density: high Voltage efficiency: high Load range: good partial load range System design: compact Degree of purity: high gas purity Dynamic: high dynamic operation Response: rapid system response	Technology: new and partially established Cost: high cost of components Catalyst type: noble Corrosion: acidic environment Durability: comparatively low Stack: below MW range Membrane: limited and costly Commercialization in near term

Table 5 – Advantages and disadvantages of Alkaline and PEM technology for hydrogen production [8]

The logical breakdown of the costs associated to liquid hydrogen to be exploited in future highspeed aerospace vehicles. At first, gaseous hydrogen production cost shall be assessed, which includes the Capital Expenditures (CAPEX), directly linked to the Investment cost, the Electricity Expenditures (EEX) requested to run the electrolysers and the Operational Expenditures (OPEX) associatead to the costs of operating and maintaining the infrastructures. Indeed, the main goal of the cost estimation is to evaluate

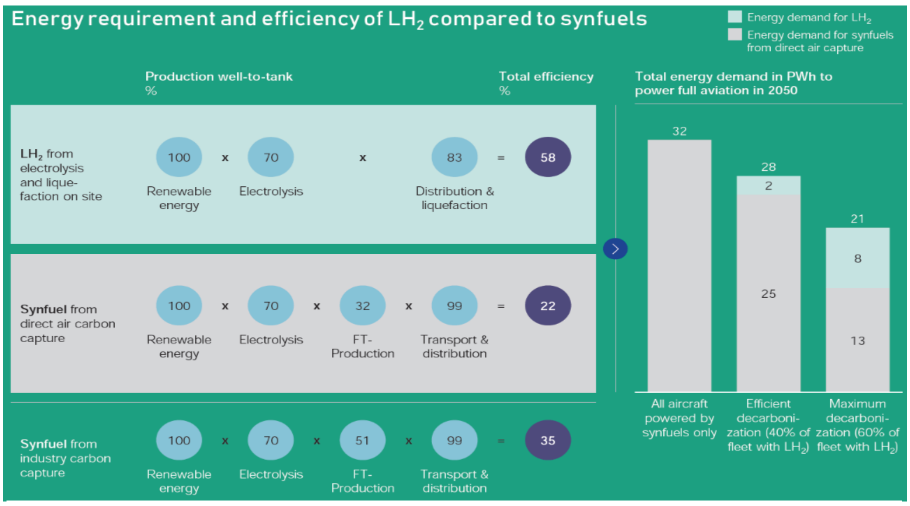


Figure 53 – Energy requirement and efficiency of LH2 compared to synfuels [39]

the Levelized Cost of Hydrogen (LCOH) defined as the present value of the price of the produced hydrogen [57]. The LCOH can be easily estimated once CAPEX, EEX and OPEX are known.

In addition to that, the cost of liquefying the hydrogen can be estimated. Then, depending on the specific scenario, storage and distribution costs can be predicted as well allowing.
International Energy Agency (IEA) has been considered as main reference [22] (Fig.54).

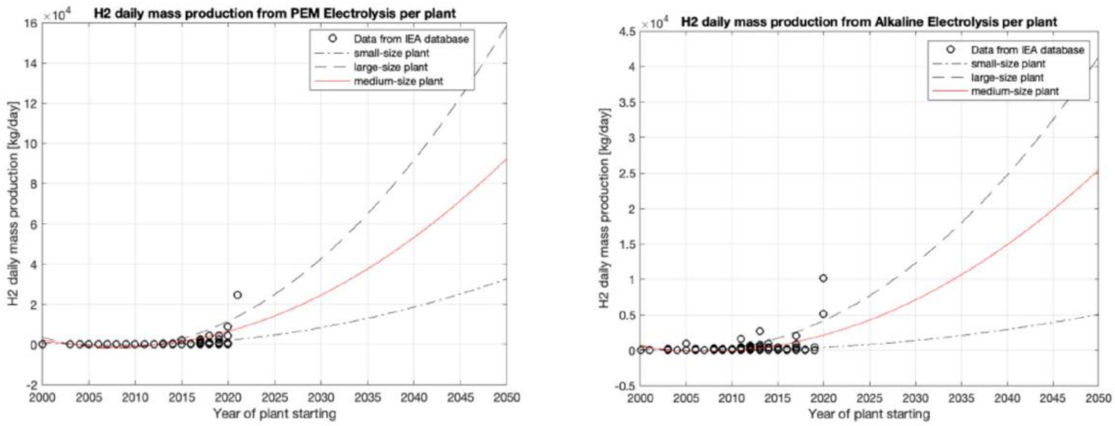


Figure 54 – Previews the future of the production scenario of hydrogen produced per day [8]

LCOH	Current scenario (2020) [€2019/kg]	Near-future scenario (2030) [€2019/kg]	Long-term future scenario (2050) [€2019/kg]
H_2 from PEM electrolysis (electricity from grid)	4.73	4.41	4.21
H_2 from Alkaline electrolysis (electricity from grid)	3.34	2.08	1.47
H_2 from PEM electrolysis (electricity from renewables)	1.18	1.04	0.91
H_2 from Alkaline electrolysis (electricity from renewables)	0.79	0.47	0.31

Figure 55 – Levelized cost of gaseous hydrogen [8]

Depending on the type of technology considered, the cost of the investment might dramatically impact the final cost of hydrogen as fuel.
To build a new infrastructure for H2 extraction can be expressed as function of the technology adopted, the size of the plant and the year of development. Focusing on electrolysis processes, the main expenditure to obtain H2 is for sure related to the electrical power demand to extract the molecules from water (EEX). EEX strongly depends on the geographical location of the plant. For example, grid electricity in Europe is almost twice as expensive as in US.
Operational Expenditures (OPEX) dependency from the plant size and are less affected by the geographical location of the plant (OPEX is about 5% of the initial CAPEX). Knowing this value is possible to estimate the overall cost per kg of gaseous hydrogen production using the formula:

$$LCOH = (CAPEX)GH2 + (EEX)GH2 + (OPEX)GH2$$

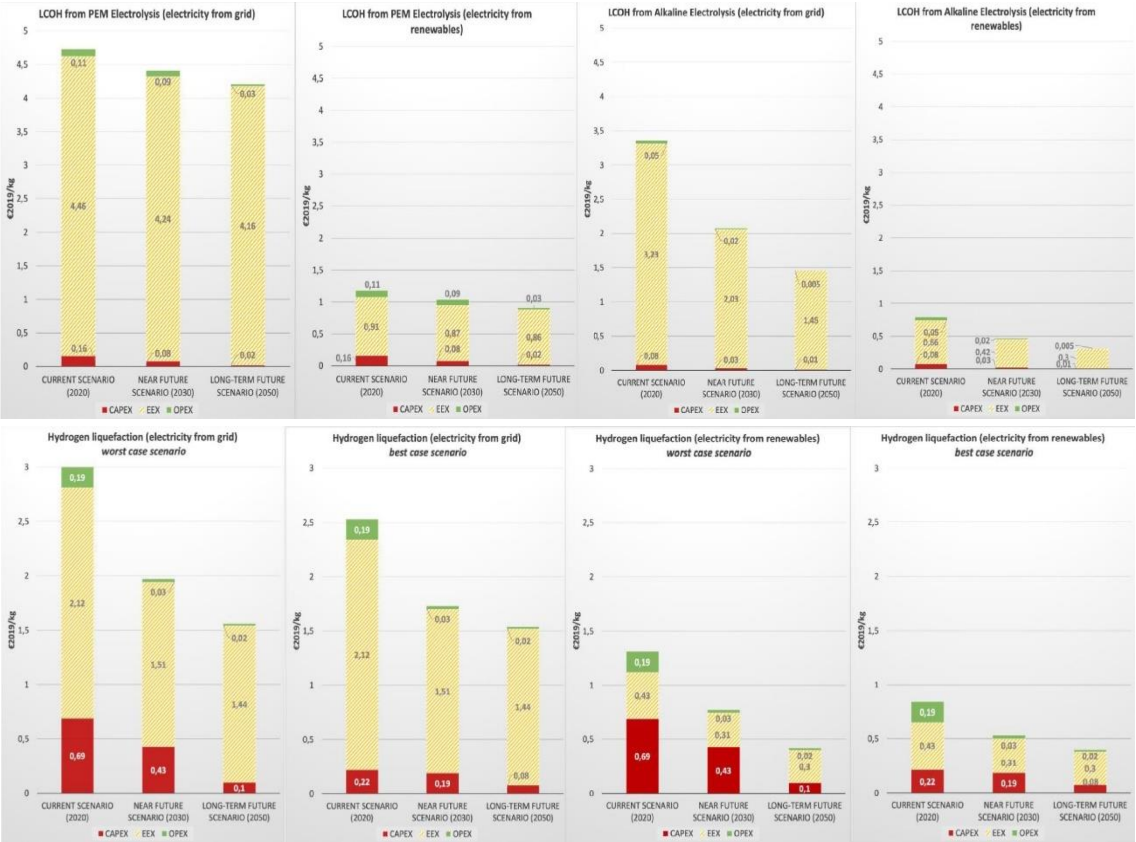


Figure 56 – TLC and LCOH comparison whit different energy method and source [8]

Another Hydrogen cost is for liquefaction. For liquefaction the cost model is the same show before. In detail, to convert gaseous hydrogen into liquid, current liquefier systems are based either on the Reversed Helium Brayton cycle (for small liquefaction capacities) or on the hydrogen Claude cycle (for larger liquefiers capacities).

According to data reported in [29], only Claude cycles will be adopted in the future considering the increased size of the plants considering the high amount of LH2 request by the aerospace sector.

	Current sce-nario (2020) [€2019/kg]	Near-future scenario (2030) [€2019/kg]	Long-term future scenario (2050) [€2019/kg]
Total liquefaction cost (electricity from grid)	2.53–3	1.73–1.97	1.52–1.79
Total liquefaction cost (electricity from renewa-bles)	0.84–1.31	0.84–1.31	

Figure 57 – Total liquefaction hydrogen cost [8]

Reference [30] and [31] have been used to estimate a plausible range of values for the investment cost of a liquefaction plant.
The liquefaction process cost is mainly driven by the electrical power consumption. The Total Liquefaction Cost (TLC) can be estimated using the formula:

$$TLC = (CAPEX)LH2 + (EEX)LH2 + (OPEX)LH2$$

In addition to the costs seen so far, the costs related to the transport and storage of LH2 are also to be taken into account. Apart from being associated to a relevant level of risk, the transport and storage of hydrogen as cryogenic liquid imposes some technical and operational challenges to maximize the cost effectiveness of the overall set of activities.

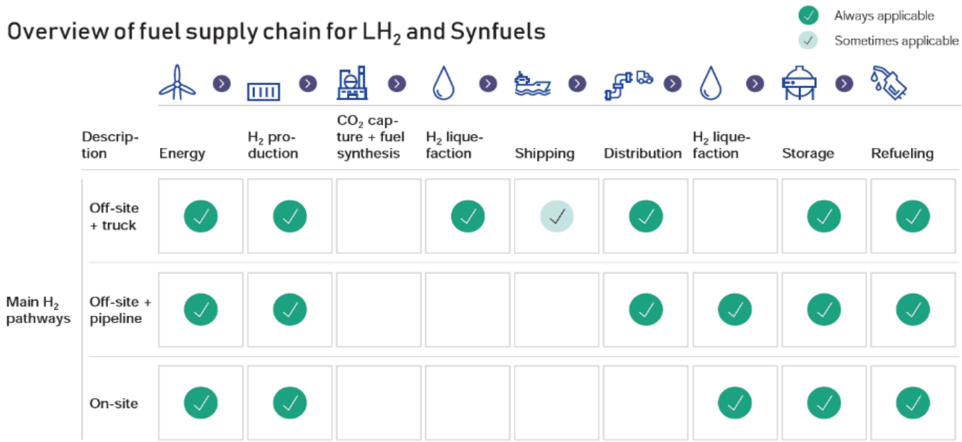


Figure 58 - Overview of fuel supply chain for LH2 and Synfuels [39]

The identification of a proper location for the production plant is a prerequisite to properly assess the impact of distribution costs on the final fuel price.
it might be cost-effective to locate it in the vicinity of the airport and to plan for an appropriate distribution. According to [32], three viable options to transport liquid hydrogen can be considered:

- Vacuum-Jacketed pipeline (economical method for distances under 75 km);
- Truck-trailer;
- Railroad tank car.

Transport pipelines of liquid hydrogen are only viable in case of large volumes and shorter distances, but will not be advantageous due to the high evaporation losses caused by heat entry. Actual natural gas pipelines can be converted to hydrogen gas with a limited impact onto infrastructures, replacing compressors and gaskets [36]. In this case, liquefaction facilities are required at the airfield.
It is envisaged that the delivery of LH2 to the aircraft would be done by tanker trucks and pipelines. Actual refueling systems would have to be converted to deliver the cryogenic hydrogen.

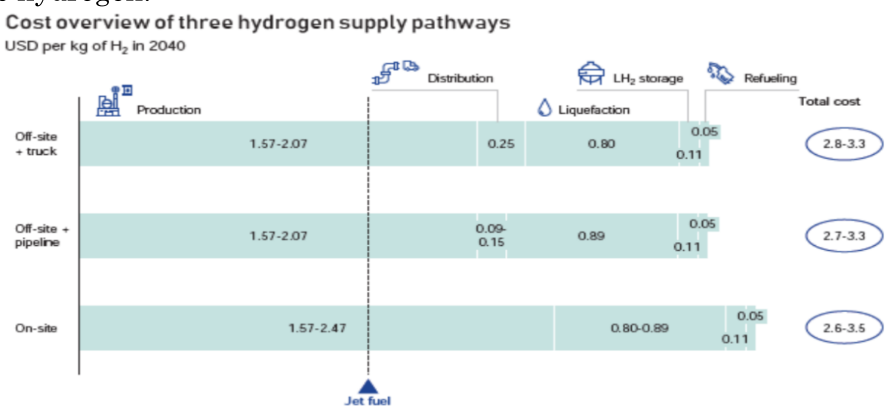


Figure 59 – Cost overview of three hydrogen supply pathways [39]

The already available hydrogen at the airport could be exploited by all ground vehicles and machines, such as buses and baggage trucks Figure 30 (pag.44). Synergies between LH2 aircraft and other hydrogen applications inside or outside airports should, therefore, be considered will increase the overall hydrogen demand at the airport, and hence cause economy of scale effects [33].

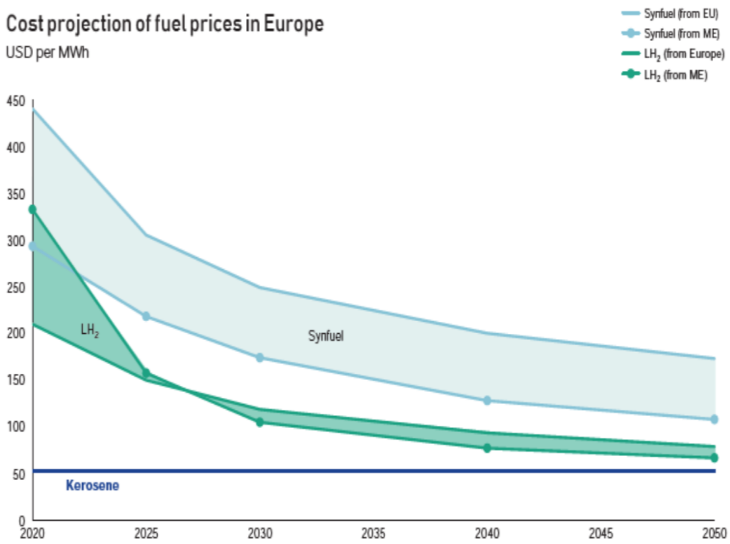


Figure 60 – Cost projection of fuel prices in Europe for LH2 and Synfuel [39]

5.1.2. Fuel Weight Ratio

The second term considered is W_{fT}/W_{GTO}. It is a ratio between a total fuel mass and total take-off weight. Wft is the total fuel weight on board. It considered in addition to the fuel needed to the mission (Wf) also the contribution of the additional reserve fuel and the quantity of liquid hydrogen necessary for compensate the boil-off phenomena (liquid hydrogen evaporate at 20 K causing different problems such as the formation of ice in the orifices of the feeding system and the non-use to power the engines, for this is required an important insulated layer in order to minimized this phenomena).

The fuel reserve is generally subject to current legislation. This must provide for the achievement of an alternative airport in the event that the main one is not available

or for guaranty an extend duration of the flight.

In preliminary design phases, the fuel reserve is a percentage of the total fuel on board (Kr).

For LH2, is very important consider in the W_{fT} the boil-off phenomena. It was not considered by the NASA report [2]. While, such as fuel reserve, it is considered as a percentage of the total fuel weight ($Kb\text{-}o$)

It is possible to write:

$$WfT = (1 + KR + Kboff)\, Wf$$

5.1.3. Payload Weight Ratio

The third parameter considered in the analysis of the fuel cost equation is that relating to the WPL/ WGTO ratio between the payload mass and the total take-off mass. This ratio should be multiplied with the load factor LF (expressed in %), that shows an average value of the payload present in each flight. Generally, the aircraft is not full every time and average value for the payload mass is required for the estimation. The load factor LF is a coefficient that indicates the average filling that is obtained during a flight in respect of the maximum capacity of passengers WPLmax. It is important that this higher level remains as high as possible for airlines, so that they can maximise revenue per flight.
It is possible to write:

$$WPL = LF * WPL\text{max}$$

In both of these relations it is possible to observe the term linked to the total take-off mass of the aircraft WGTO also appear. The numerators seen above are a function of this one.
In fact, once defined, this term cannot be changed, while the various terms that compose it up can change, including the weight of the fuel and that of the payload.
It is possible to write that:

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

The aircraft performances are linked to the fuel on board. Considering a fixed value for maximum take-off weight, if payload weight increased the fuel weight should decrease. Consequently, we have a flight range reduction.
The reference [59] show how the quantity of fuel on board depends on the operational range and on the mission profile.
The relationship between mission fuel weight, payload weight and range for a fixed maximum take-off weight as show in the figure below.

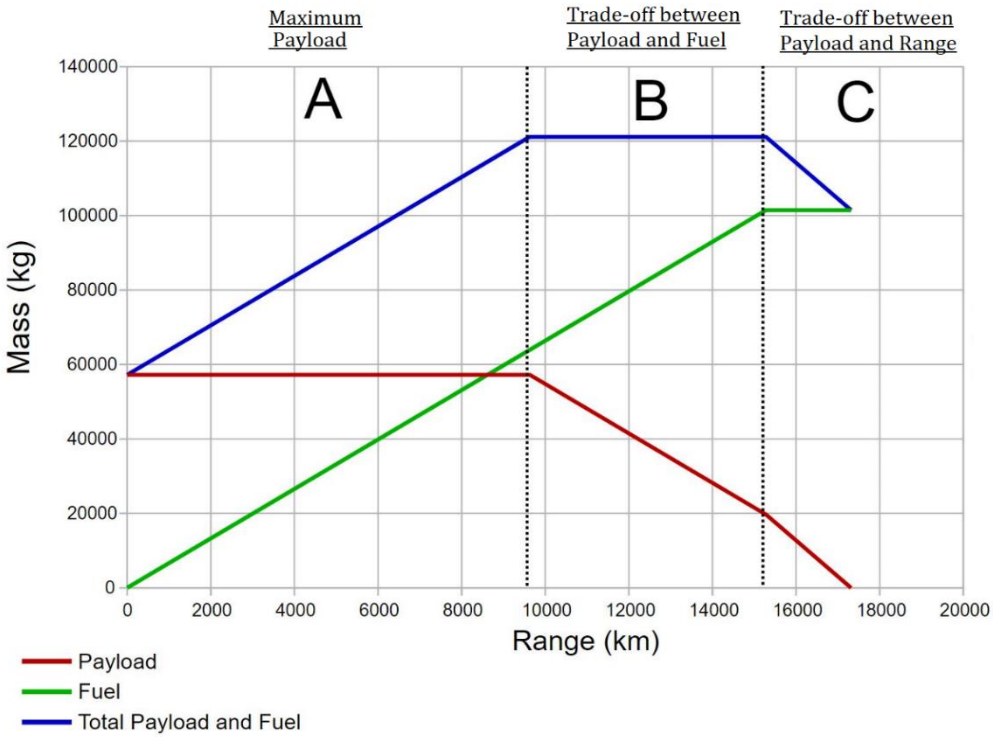


Figure 61 – Combined Payload-Fuel-Range Diagram [40]

If payload weight increases, the range decrease, because the quantity of fuel on board is decreased (the quantity of fuel needed to accomplished the mission depends furthermore on the cruise technique adopted).
We can observe that for reach the maximum range, the fuel weight is the highest value as possible and that on the contrary the payload weight is zero (solution unacceptable because the payload (people or cargo) is necessary for makes profits). In this analysis the range is fixed because the mission is to connection two specific cities.

5.1.4. Operative Range

The last element in Fuel CERs is the range of the aircraft.
This term is an important item not only in the fuel cost but in the direct operating costs. In fact, if it increases, the DOC decreases.
It is very important for the airline companies to monitor their economic performances evaluating the DOC per kilometre or per nautical mile.
Generally, two important parameters are evaluated:
- Revenue Passenger Kilometres (RPK) shows the number ok kilometres flown by paying passengers;
- Available Sets Kilometres (ASK) is the total of passenger kilometres necessary to determine a specific economical revenue;

Both parameters depend on the kilometres travelled by the aircraft.

5.1.5. Fuel CER Update

In this case the NASA [2] fuel cost CER it has not been modified as it simply goes into account the fuel consumed during the flight. The price of fuel per kg is the key factor driving this equation and its value as seen depends on numerous factors. However, in order to still ensure flexibility and immediacy in the use of this equation with both conventional fuel and liquid hydrogen, it was decided not to further decompose the term Cf.

5.2. Maintenance cost driver factors

The formulation of maintenance costs reported in the NASA method [2] is closely linked to six cost items. Each of these items (more or less independent of each other) has a certain weight on the final cost. It should be noted that in this analysis the two entries relating to the Ramjet will not be considered.
For these items, it is evaluated the labor cost, and the cost of materials required for the maintenance activities.

In the NASA study [2] is report two propulsive system, a turbojet for flight at low and ramjet for fling at high Mach number. Nevertheless, for supersonic flight is more convenience using just the propulsions system based on turbojet. For this during the next analysis, only turbojet maintenance cost equations will be considered.
In all the formulas that we are going to analyze at the denominator are placed the same terms already seen for the formula of the cost of fuel, so a further repetition of the analysis of these terms will be omitted, focusing only on the terms previously not analysed (some considerations about the maintenance factors are made).
Considering the case of the structure for liquid hydrogen aircraft, the innovations can be the fuselage type and the configuration. Different fuselage shapes and size have different weight, features and aerodynamic performances.
In the maintenance equations, the aerodynamic performances are expressed by the aerodynamics efficiency included in the range (explicable through the Breguet formula).
In all mathematical relationships, it is present the time of flight and the range.
The time of fight is directly linked to the range and to the type of mission. This, lead to decrease direct operating costs (including maintenance cost) if the range decrease [3]
As suggest NASA study [2], all weights in the relationships can be expressed how a fraction of the maximum take-off weight:

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

Through this relation, the weight of the engines in the equations of maintenance is implicit in W_{GTO} term. Nevertheless, they are strongly dependent on the acquisition costs. The cruise Mach is reported in the formula of the maintenance material cost of the airframe (between this factor and the maintenance cost there is not a linear relation).
However, the formulation for the calculation of NASA maintenance costs [2] is based on coefficients of working hours performed per hour of flight and per flight proposed by the ATA in 1967 [1]. These coefficients are absolutely not aligned with market values. Precisely for this reason, in fact, within the new calculation model, some CERs will be adopted for the calculation of maintenance costs that make references to more recent values more aligned with what are the market values.

The NASA equation [2] for the maintenance is:

$$DOC_M = DOC_{M/AF/L} + DOC_{M/AF/M} + DOC_{M/TJ/L} + DOC_{M/TJ/M} + \cancel{DOC_{M/RJ/L}} + \cancel{DOC_{M/RJ/M}}$$

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;

All factors are reported in international unit system and the DOC formulas are expressed in cost per ton-mile.

<u>DOC airframe and subsystems maintenance labor:</u>

$$DOC_{\mathrm{M/AF/L}} = \frac{(3.22 + 1.93\, t_F)\left[0.05 * \left(\frac{W_{AF}}{W_{GTO}} + \frac{W_{AV}}{W_{GTO}}\right) + \left(\frac{6}{W_{GTO}} - \frac{630}{\left(\frac{W_{AF} + W_{AV}}{10^3} + 120\right) W_{GTO}}\right)\right] M^{\frac{1}{2}}\, r_L}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

<u>DOC airframe and subsystems maintenance materials:</u>

$$DOC_{\mathrm{M/AF/M}} = \frac{(4.52\, t_F + 9.04)\left(\frac{C_A}{W_{GTO}} - \frac{C_{TJ}}{W_{GTO}} - \cancel{\frac{C_{RJ}}{W_{GTO}}}\right)}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T\, 10^3}$$

<u>DOC Turbojet engine maintenance labor:</u>

$$DOC_{\mathrm{M/TJ/L}} = \frac{\left(\frac{T}{W}\right)_{GTO} (1 + 0.3\, t_F)\left(\frac{8.6}{T_{TJ}/10^3} + 0.087\right) r_L\, K_{LTJ}}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

<u>DOC Turbojet engine maintenance material:</u>

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

Where:

t_F = time of flight [hr];

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

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

M = Mach number;

r_L = average labor rate for all personnel involved in maintenance [$];

C_A= Acquisition cost of aircraft;

C_{TJ} = Acquisition cost of turbojet engine;

$(T/W)_{GTO}$ = thrust to weight ratio at take-off;

T_{TJ} = thrust of turbojet engines per engine (sea static level) [N];

K_{LTJ} = maintenance labor ratio for turbojet engine;

K_{MTJ} =maintenance material ratio for turbojet engines.

5.2.1. Time of flight

The first term considered is the flight time. This is also linked to the mission, to the range is to the type of strategy that is adopted during the latter (e.g., variation of thrust-to-weight ratio or increases the lift-to-drag ratio). Its variation generally impacts the amount of fuel on board and consequently leads to a change in the maximum take-off weight with the same trend.
Different time of flight has effect on the maintenance coefficients, its variation in fact leads to a consequential variation of the flight cycle and consequently of the cycle of loads to which the aircraft is subjected. As is known, in fact, the greatest loads during a flight are obtained during landing. With the same aircraft utilization in hours per years, flights of shorter duration lead up to a major number of landings per hour, for that these loads occur more frequently, thus leading to a consequent increase in inspections and hours of maintenance of the vehicle.

5.2.2. Aircraft Weight Fraction and Avionic Weight Fraction

The terms considered are W_{AF}/W_{GTO} and W_{Av}/W_{GTO}. The first one is a ratio between airframe and subsystems weight excluding engines and avionics and total take-off weight while the second is a ratio between only the avionics subsystem weight and total take-off weight.
As for the weight of the structure and subsystems, here a technological factor of maximum importance is the use of innovative materials. In fact, these can have a significant impact on the weight of the structure of the aircraft and consequently also on its total weight. Think of the use of carbon fiber compared to the classic aluminium alloys used for the construction of the structure.
It should also be considered that in the case of liquid hydrogen aircraft the introduction of new subsystems than traditional aircraft have can change the maintenance procedures.
As far as avionics is concerned, today it plays a role of primary importance in modern aircraft. Although not recognizable its clear increase in terms of weight than the

aircraft of the previous generation, the latter thanks to the modularity began to cover an increasingly important wheel inside the sail. This is demonstrated by the simple fact of representing one of the large share-part for the acquisition price of the aircraft not that also one of the most expensive elements subject to maintenance (in modern aircraft it can come to be the second item of maintenance expenditure of the aircraft, placing itself immediately behind the cost of engine maintenance which, however, I have a much higher rate of wear).
All weights in the formulation contribute to modify the maximum take-off weight.
Finally, it is possible to observe a linear relationship between the increase in the weight of the components and the operating cost associated with the vehicle.

5.2.3. Mach

Formula obtained from an appropriate conversion of the ATA formulation [1] valid up to the supersonic case in the field of hypersonic velocities, where the extension of validity of the formula is obtained through the term linked to the Mach number (max=1 for subsonic case).
Using this formulation for aircraft with a cruising speed of M=6 leads to an increase in costs of up to 2.4 times the cost of subsonic aircraft.
It is reasonable to this point to think that with regard to supersonic aircraft the value will be within this range of values.

5.2.4. Average labor rate

It represents the hourly wage of the maintenance workers. If the salary increases, the maintenance labor cost increase too. For all maintenance personnel, the ATA [1] gives $4.00 as the input value for average labor rate in its formula during 1967.
Wanting to go into detail about this cost item, referring to what was published by IATA in 2013 [[41]] we can see how there are 3 important aspects to be considered:

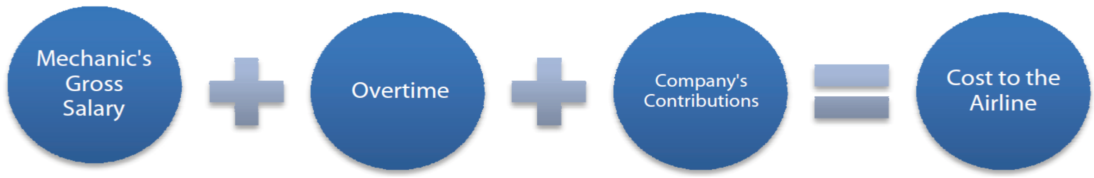


Figure 62 – Various contribution in IATA Labor Rate [41]

employee's gross salary, the employee's overtime pays, and the company's contributions for the employee's benefits
The total cost of the employee (including overtime pay) will be divided by the total number of hours (scheduled and overtime) for that year.
In order to determine the total cost of the employee for the year, on an hourly basis, the total cost must be divided by the total number of hours worked during the year, including overtime.

		Annual
Average Gross Salary • Assume $15.38 /hr • Scheduled at 2,080 hrs per year • ($15.38 x 2,080 = $32,000.00)		$32,000.00
Company's Contributions – Benefits		$10,000.00
Overtime Allocation (if applicable) • Assume overtime is paid at 1.5 x regular time • ($15.38 x 1.5 = $23.07) • Assume 100 overtime hours have been worked • ($23.07 x 100 = $2,307.70)		$2,307.70
Total Cost of Employee for the Year		$44,307.70
	Annual	**Hourly (2,180 hrs)**
Total Cost of Employee for the Year	$44,307.70	$20.33

Figure 63 – IATA Total Hourly Cost of employee in the year [41]

It is important to be able to determine the productivity of employees as this will help determine how much maintenance employees are costing an airline (or maintenance entity) relative to the work that they are performing. Productivity is also used to estimate the number of employees required to perform certain tasks.

Productivity is determined by the number of hours that an employee is working directly on his/her duties. There are times throughout the year when employees are not performing direct labor however are still being paid. There are 2 scenarios where this occurs:

- Employee is physically absent from the workplace (i.e. weekends, vacation, public holidays, sick leave, etc.)
- Employee is physically present but performs other tasks (i.e. training, meeting, morning briefings, breaks, etc.)

It is important to note that third parties will typically pay for services by the hour and they will only pay for time when the employees are physically working on maintenance tasks, (i.e. during the "productive time"). Since third parties will only be paying for productive time, it is crucial to be able to adjust for that and determine how much the employee is costing the employer during non-productive time. The extra costs that are incurred during non-productive time will be allocated to the productive hours in order to come up with an adjusted cost per productive hour that takes into account the hours that the employee is getting paid, but not working directly on maintenance activities.

There are two key reasons for airlines to determine the adjusted labor rate of their employees. First, they can compare the cost of performing maintenance in-house versus outsourcing the tasks. For example, if an airline can negotiate to have a third party perform work for them below their adjusted labor cost5 then they may want to consider outsourcing as it will be more cost effective. The second reason they should determine the adjusted labor cost is if they have unused capacity and are interested performing services for third parties. By charging a rate equal to the adjusted labor cost they will break even, and any charge above that will be profit.

A two-step calculation is required to determine the adjusted labor rate. First, one must determine the productivity adjustment factor. This factor is the fraction of total scheduled working time over total productive time. This number will now be multiplied by the cost per hour, per employee, that was previously determined to figure out the adjusted cost per employee (per hour).

This cost is important as it will be crucial in determining the break-even point if ever an airline would like to sell their technical services to third parties.

Productivity Adjustment Factor = 2,080/1,540 = 1.35
Adjusted Hourly Labor Rate = $20.18 x 1.35 = $27.24

Figure 64 – IATA Adjusted Hourly Labor Rate [41]

This cost of $27.24 (F.Y.2013) will have to be updated to be used correctly for the calculation of the cost of maintenance.
Through the reference [54] it is possible to see that from 2013 to today on the USD there has been an average inflation rate of 1.79% and cumulative inflation of 15.23%, so the previous cost must be multiplied by actualization coefficient of 1.152, arriving at a value of maintenance labor rate di $ 31.39 (F.Y.2021)
Refer to [54] we can also update the value on the ATA [1] report. From 1967 to 2021, the price is actualized by a multiplicative coefficient of 8,047 (due an average inflation rate of 3.97% and cumulative inflation of 704.67% on USD) thus leading to a maintenance labor rate value of $32.19 (F.Y. 2021). It should be emphasized that this value, as calculated in 1967, if updated, follows almost perfectly the values of current salaries (between it and the IATA reference there is only a gap of 2.49%).

5.2.5. Acquisition cost of Aircraft and turbojet engine

In maintenance material equation, the acquisition costs of the aircraft and of the its subsystems are present.
This increases the acquisition cost of the aircraft, defines the cost of the materials of the vehicle.
As report in NASA method [2], there is relationship with the acquisition cost and the cost of maintenance.

Aircraft model	Price (M$)	OEW (tonnes)	Price $ / kg
A380	356,3	276,8	1.287
A340-500	250,8	170,9	1.468
A340-600	263,8	177,8	1.484
787-8	166,25	110	1.511
787-3	152,75	101	1.512
747-8	300,5	191,1	1.572
A318	62,5	39,5	1.582
A330-200	191,4	119,6	1.600
777-300ER	271,75	167,8	1.619
737-700	64	37,6	1.702
A330-300	212,4	124,5	1.706
787-9	199,75	115	1.737
A340-300	228	130,2	1.751
A319	74,4	40,8	1.824
A320	81,4	42,6	1.911
A321	95,5	48,5	1.969
A350-900WXB	254,5	115,7	2.200
		Avge.	1.673

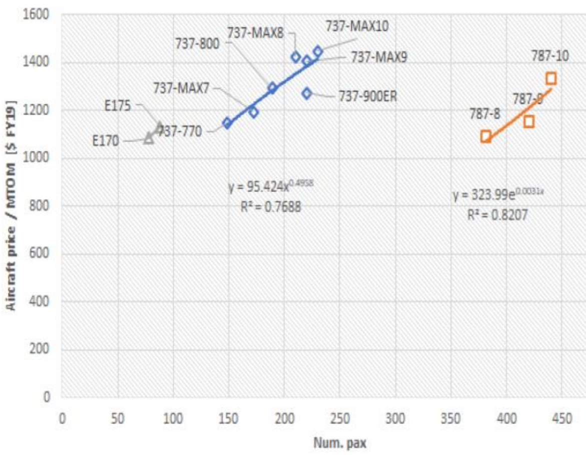


Figure 65 – Civil Aircraft MTOM - Market price comparison [6]

As report in NASA study [2], Acquisition costs for the total aircraft C_A are expressed by the formula

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

Where:

C_A = total cost of aircraft [$];

C_{AF} = cost of airplane less engine and avionics [$];

~~C_{RJ} = cost of ramjet engine set per aircraft [$];~~

C_{TJ} = cost of turbojet engine set per aircraft [$];

C_{AV} = cost of avionics [$];

W_{GTO} = gross take-of [kg].

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

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

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

Where:

W_{AF} = airframe weight [kg]

M = cruise Mach

N_{TJ} = number of turbojets

T_{TJ} = thrust of the turbojet [N]

$(T/W)_{GTO}$ = thrust to weight ratio at the take-off

W_{AV}= avionics weight [kg]

It is necessary to underline how the various items that make up the total cost of acquiring the vehicle are independent of each other and how they refer essentially to the weight of the items or to other factors such as the thrust. However as highlighted above, one a parametric cost estimation based simply on weight lends itself poorly to all cost especially for engine and avionics. In fact, the latter given its technological evolution it has increased its value by freeing itself from the weight thanks to the modularity of the equipment and the high level of technology reached by the latter. It will therefore be necessary to introduce price discounting coefficients into the model, making sure that the acquisition prices obtained through the NASA formulation [2] are aligned with the reference prices currently on the market, especially as regards avionics costs (about twice the value obtainable from the NASA model [2]) and for engines (about four times).

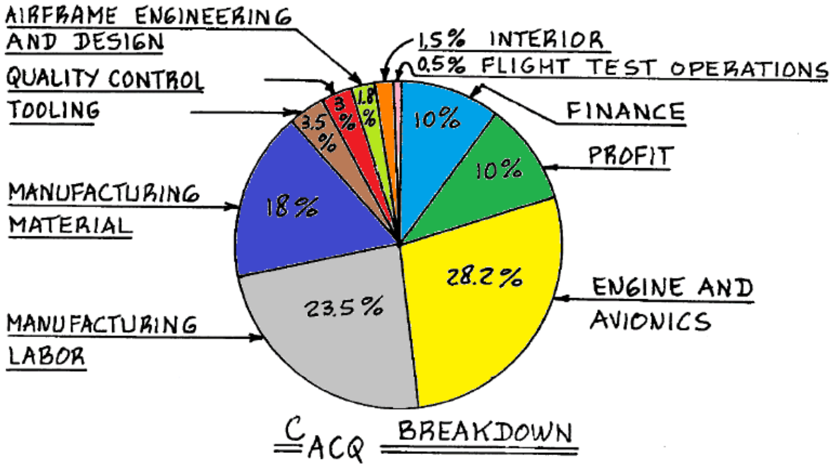


Figure 66 – Roskam DOC Breakdown [3]

Moreover, a change in the number of airplanes built modifies the production costs and the acquisition price. An increase in production can lead to the gain of a discount on the basic and consumable material and to a reduction in the construction and assembly times of the vehicle (as described by the learning curve especially with regard to manual operations).

5.2.6. Thrust to weight ratio at take-off

Generally, the relationships between the maximum take-off thrust of an aircraft and its mass is linear as show in the figure 68.

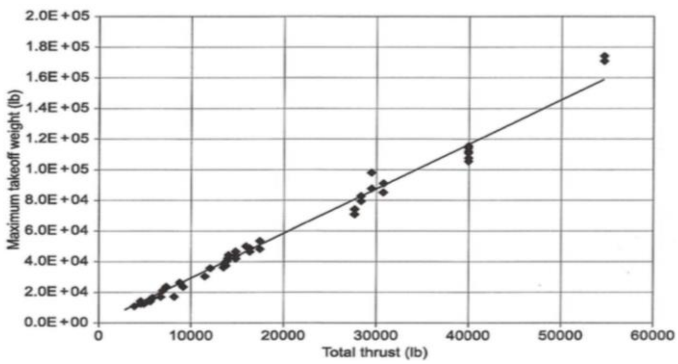


Figure 67 – Maximum take-off weight – Total thrust [42]

It should also be specified that the ratio pushed on take-off is also linked to the wing load. In fact, the choice of a power unit with a suitable thrust to weight ratio must be made in the first instance through the satisfaction of all the requirements set by the matching chart.

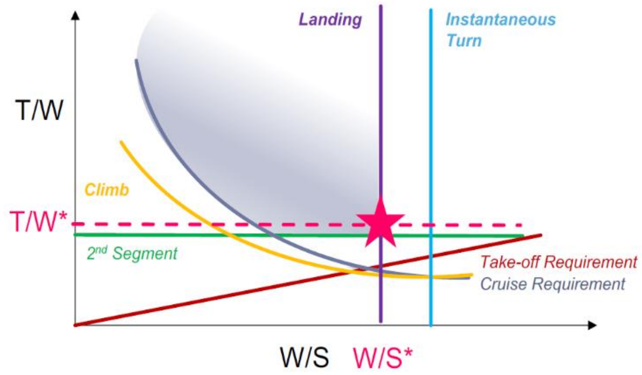


Figure 68 – Matching chart [7]

5.2.7. Thrust of turbojet engines

The cost of aircraft is linked to cruise speed. That's because it must guarantee high-level performances in a safety way. If speed increasing, the various parts of which it is composed the aircraft and the materials must be strong to support this increased load and this lead to an increased maintenance cost. With the speed rise is possible to observe a decreasing of aerodynamics efficiency. That's because the drag coefficient increases with the Mach number until it reaches a constant value, as shown in the figure below

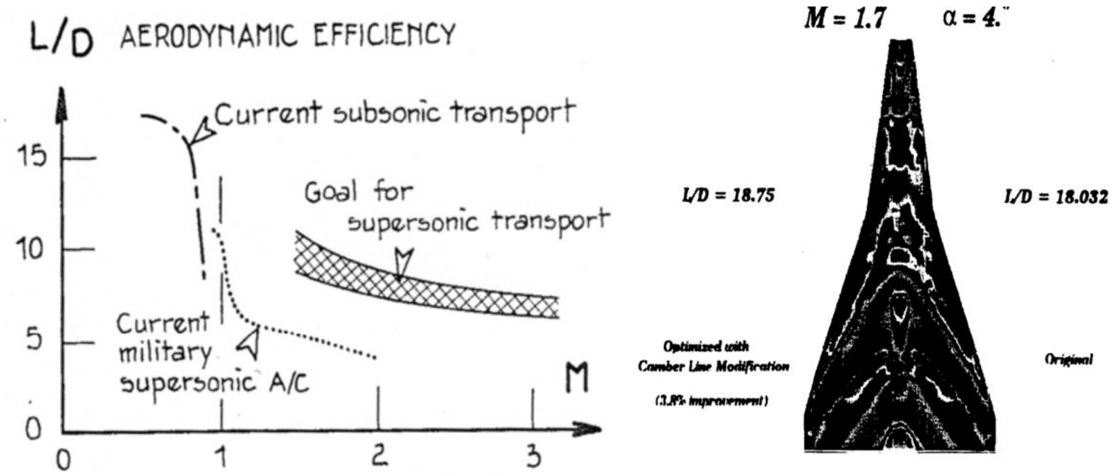


Figure 69 – Mach - Aerodynamic efficiency diagram [7]

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.

5.2.8. Maintenance material and labor ratio for turbojet engine

Maintenance activities generally require variable timing depending on the operating methods chosen by the airline that led to a change in the time of use of the aircraft. The latter are therefore not easily estimated.
The ATA formulas [1] on which the DOC formulas are based covered supersonic (SST) as well as subsonic turbojets and utilized coefficients in their supersonic and subsonic formulas which gave an equivalent value of KLTJ and KMTJ of approximately 1.7 to 1. A value of 2.0 to 1 has been used by NASA [2] in the demonstration calculations for the HST because the HST turbojets are estimated to have higher maintenance requirements per hour of operation than the SST turbojets.

5.2.9. Maintenance CERs update

In this case the equation of estimation of maintenance costs has been completely replaced. The choice to replace these relationships is above all the result of the fact that this historically speaking has never really lent itself to what were the real maintenance costs incurred by the SST. As is well known, in fact, these costs can even reach 50% of THE DOC.
For this reason, it was preferred to replace almost all the equations with new ones that had more modern coefficients inside them and that better represented what are the real maintenance costs. These equations are obtained from reference [62] in turn derived from the [3]

$$DOC_{\mathrm{M/AF/L}} = \frac{r_L * \left[3 + \left(0.067 * \left(\frac{W_{AF} + W_{AV}}{1000}\right)\right)\right]}{\left((LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T\right)}$$

$$DOC_{\mathrm{M/AF/M}} = \frac{[30 + 0.79 * 10^{-5} * (C_{AF} + C_{AV})]}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

$$DOC_{\mathrm{M/TJ/L}} = \frac{r_L * N_{TJ} * 1.3 * 0.718 + \left[0.0317 * \left(\frac{W_{GTO} * 2.2046 * \left(\frac{T}{W}\right)_{GTO}}{(N_{TJ} * 1000)}\right) * \left(\frac{1100}{TBO} + 0.1\right)\right]}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

$$DOC_{\mathrm{M/TJ/M}} = \frac{1.3 * 5.43 * 10^{-5} * (C_{TJ} * TJ_{sppf})}{\left(0.021 * \left(\frac{TBO}{100}\right) + 0.769\right) * (LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

Where:

TJ_{sppf} = Turbojet Spare Part Price Factor;

TBO = hours between engine overhaul [hr]

Through this new set of equations, we implicitly consider the number labor hours in block hours and materials required for the engines and airframe. The labor cost for engine and airframe maintenance is a function of the labor hours and the labor rate. The labor hours for engine maintenance are a function of a total take-off thrust, the number of engine and the hours between engine overhaul while the labor hour of airframe is a function of airframe weight.
For airframe maintenance materials the cost is based on airframe price, while, the cost of material required for engine maintenance depends on the factor for the attained period between engine overhaul, used to determine the material cost for engine along with the engine price and the engine spare part price factor.
The total maintenance cost (as a NASA CER [2]) is the sum of this item.

5.3. Crew cost driver factors

As a NASA method report [2], the CERs of crew cost is:

$$DOC_C = \frac{320}{0.725\ (LF)\ (W_{PL})\ M\left(\frac{V_B}{V_{CR}}\right)}$$

Where:

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

This formulation derives from ATA formula [1] for crew cost, expressed in $/block hr:

$$DOC_C = \left(0.05\ \frac{W_{GTO}[lb]}{1000} + K_C\right)$$

Where K_C for international plane with three-man crew:

- Turboprop: 118
- Turbojet: 155
- SST: 200

These costs were derived from a review of several representative crew contracts. based on this review, yearly rates of pay were arrived at which were used with welfare, training, travel expense, and crew utilization factors to produce the crew cost equation herein.
In 1967 a typical value of crew cost in $/block hour for a 450000 lb gross take-off weight aircraft was:

- Turboprop: 141
- Turbojet: 178
- SST: 223

In NASA report [2] this value was actualized at 1973 and an extrapolation was made to obtain HST value (320 $/block hour). This value is use in the NASA formula [2] where the denominator is use to convert the DOC in $/ton-mile.
Through the reference [15] it is possible to see the average total cost for the flight crew nowadays is around $1300 $/block hour (referring to the cost of the pilot and the co-pilot for turbojet aircraft).
The use of this value in the formula proposed by NASA [2] could bring the costs of the crew to reasonable values. It should also be remembered as previously done that the expense for the flight crew is still the least influential among the various items of direct operating cost.

5.3.1. Crew CER Update

For update the NASA CERs [2] in the new DOC model, it simply replaces the value of 320 obtained from the previous extrapolation conducted by NASA with the original formula proposed by ATA in 1967 [1]. Here the introduction of the coefficient 2.205 is used to ensure the use of units of measurement in the international system. This formula is then appropriately updated through a CPI - Consumer price Index (Trend of the inflation index against the US dollar between January 1967 and January 2021 obtain from reference [43]).

$$DOC_C = \frac{CPI * \left(0.05 \dfrac{W_{GTO} * 2.205}{1000} + K_C\right)}{0.725\ (LF)\ (W_{PL})\ M\left(\dfrac{V_B}{V_{CR}}\right)}$$

Total Cockpit Cost per Block Hour - ALL AIRCRAFT

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
American	819	$ 821	$ 846	$ 764	$ 755	$ 827	$ 1,034	$ 1,115	$ 1,236	$ 1,281	$ 1,352
Continental	667	$ 654	$ 694	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Delta	691	$ 799	$ 837	$ 899	$ 1,039	$ 1,081	$ 1,104	$ 1,261	$ 1,314	$ 1,333	$ 1,373
Northwest	899	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
United	754	$ 741	$ 697	$ 753	$ 929	$ 1,101	$ 1,100	$ 1,249	$ 1,277	$ 1,337	$ 1,379
US Airways	567	$ 559	$ 554	$ 564	$ 570	$ 786	$ -	$ -	$ -	$ -	$ -
American West	-	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
--sub Network	**736**	**$ 741**	**$ 756**	**$ 774**	**$ 868**	**$ 982**	**$ 1,076**	**$ 1,203**	**$ 1,274**	**$ 1,315**	**$ 1,367**
Southwest	630	$ 691	$ 700	$ 698	$ 743	$ 807	$ 924	$ 963	$ 1,023	$ 1,039	$ 1,143
jetBlue	514	$ 564	$ 574	$ 614	$ 652	$ 717	$ 808	$ 796	$ 815	$ 911	$ 1,015
AirTran	387	$ 416	$ 476	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Frontier	349	$ 394	$ 427	$ 390	$ 429	$ 532	$ 700	$ 705	$ 656	$ 946	$ 896
Virgin America	298	$ 304	$ 345	$ 363	$ 423	$ 510	$ 586	$ 588	$ 746	$ -	$ -
--sub LCC	**544**	**$ 592**	**$ 612**	**$ 645**	**$ 690**	**$ 754**	**$ 865**	**$ 886**	**$ 933**	**$ 999**	**$ 1,088**
Alaska	812	$ 706	$ 719	$ 727	$ 746	$ 789	$ 783	$ 782	$ 842	$ 908	$ 947
Hawaiian	743	$ 795	$ 819	$ 901	$ 920	$ 875	$ 957	$ 945	$ 1,078	$ 1,122	$ 1,150
Spirit	427	$ 496	$ 525	$ 549	$ 526	$ 558	$ 558	$ 581	$ 565	$ 735	$ 818
Allegiant	292	$ 363	$ 426	$ 413	$ 474	$ 542	$ 565	$ 669	$ 896	$ 921	$ 871
-- sub Other	**667**	**$ 634**	**$ 659**	**$ 677**	**$ 691**	**$ 714**	**$ 717**	**$ 729**	**$ 797**	**$ 885**	**$ 921**
Total All Sectors	**681**	**$ 694**	**$ 710**	**$ 731**	**$ 805**	**$ 899**	**$ 987**	**$ 1,070**	**$ 1,131**	**$ 1,179**	**$ 1,238**

Note: Data is total cockpit cost and is not per pilot. To calculate per pilot cost, simply divide by 2. No assumption is made for relief pilot staffing.
Notes: The full effect of each Delta's and Northwest's restructuring of financials and operations are not fully reflected in 2006.
Pilot Cost includes: salaries and wages, benefits and pensions, payroll taxes and personnel expenses impacted by collective bargaining terms.

Figure 70 - Total Cockpit per Block Hour [15]

5.4. Insurance cost driver factors

In the formulation provided by ATA, the cost of insurance simply involves multiplying an annual insurance rate by the cost of acquiring the aircraft.

$$Annual\ insurance\ cost = (IR)\ (C_{HST})$$

The annual insurance rate is difficult to estimate, because it depends on the legislation and on the airline policy. Refer to the values proposed by the study NASA [2] it can be expressed as a percentage of the total vehicle cost. This value for new aircraft is usually 5% of the original acquisition cost. However, during the life of vehicle, this coefficient decreases quickly until 2% after 4 year which is given as a typical industry average.
For the acquisition cost of the aircraft, this is already seen in the expressions related to maintenance is linked to factors of size and performance of the aircraft, not that also due to the different technologies that can be adopted on the vehicle (e.g. avionics systems, particular refrigeration systems of the vehicle, use of alternative fuel systems).

Adapting this formula through the conversion parameters proposed by NASA [2] we obtain:

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

Where:

IR = annual insurance rate, [%/100];

U = aircraft utilization, [block hrs/yr.]

Aircraft utilization is the average block hours of use of the aircraft in a year. Typical utilization for industry varies from about 3000 hours to 4500 hours during normal times depending on the aircraft and air lines involved.

Average Daily Block Hour Utilization of Total Operating Fleet
All Aircraft

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
American	9.71	9.63	9.58	9.63	9.85	9.84	9.81	10.11	9.92	10.32	11.14
Continental	10.60	10.69	10.72	-	-	-	-	-	-	-	-
Delta	10.51	10.24	10.39	10.21	10.28	10.23	10.32	10.35	10.15	10.28	10.42
Northwest	9.22	-	-	-	-	-	-	-	-	-	-
United	10.79	11.01	10.71	10.65	10.46	10.42	10.39	10.28	10.44	10.74	10.82
US Airways	9.47	9.52	9.78	9.60	9.91	10.01	-	-	-	-	-
America West	-	-	-	-	-	-	-	-	-	-	-
--sub Network	**10.06**	**10.16**	**10.19**	**10.10**	**10.17**	**10.15**	**10.14**	**10.24**	**10.15**	**10.43**	**10.79**
Southwest	10.26	10.20	10.46	11.46	11.65	11.01	10.53	10.46	10.68	10.80	10.51
jetBlue	11.51	11.66	11.68	11.81	11.96	11.77	11.89	12.06	11.74	11.76	11.85
AirTran	10.99	11.04	11.04		-						
Frontier	11.73	13.32	12.40	9.94	10.08	11.45	12.39	11.95	13.41	12.34	11.56
Virgin America	12.75	13.92	12.59	13.99	12.43	11.33	10.93	10.95	11.12	-	-
-- sub LCC	**10.73**	**10.84**	**10.94**	**11.55**	**11.66**	**11.21**	**10.94**	**10.91**	**11.10**	**11.14**	**10.91**
Alaska	9.75	9.94	10.45	10.66	10.64	10.50	11.80	10.80	11.25	12.10	10.88
Hawaiian	9.18	8.96	9.69	9.63	9.79	9.48	9.62	9.82	9.95	10.02	10.16
Spirit	13.00	12.85	12.69	12.66	12.30	12.75	13.14	13.34	11.50	12.51	12.24
Allegiant	6.68	6.20	5.71	5.50	5.34	5.28	5.76	6.15	6.47	6.74	7.75
-- sub Other	**9.53**	**9.40**	**9.63**	**9.64**	**9.65**	**9.59**	**10.36**	**10.16**	**10.09**	**10.91**	**10.64**
Total All Sectors	**10.20**	**10.28**	**10.35**	**10.44**	**10.50**	**10.37**	**10.37**	**10.41**	**10.40**	**10.67**	**10.80**

Figure 71 – Average Daily Block Hour Utilization of Total Operating fleet [44]

This value provided in the NASA study [2] is still congruent with the current values as it is possible to see from the values proposed by MIT during the last decade and reported in the figure (72).

The values shown in the figure in fact refer to an average daily block hours utilization for the major American companies. These values multiplied for the days of the year you get a value close to 4000 hours of use.
However, this value cannot be used for our analysis since this value, however correct it is, is related to subsonic aircraft that require much less hours of maintenance than supersonic or hypersonic aircraft that during their mission will be subjected to much greater loads and for this reason they will undergo a much more intense maintenance activity in terms of working hours.

5.4.1. Insurance CER Update

As mentioned above, there is the complexity in administering an insurance rate due to terms often linked to external market parameters, not directly related to the aircraft as shown in the figure below

Hull	Liability
Experience of fleet	Experience of fleet
Type & value of aircraft	Departures and number of passengers (previously RPKs flown)
Experience of pilots & crew	Passenger make up
Routes flown	Routes flown, conditions of carriage operated and underlying legal situation.
Excess used	Capacity of aircraft

Table 6 – Parameters that affect the cost of the insurance policy [45]

To maintain the immediacy and flexibility of the equation, it was decided to keep the expression provided by the NASA model [2] unchanged.

5.5. Depreciation cost driver factors

Depreciation cost is an expense provided to recover the original cost of the aircraft, plus the initial stock of spare parts, over an assigned depreciation life of the aircraft (The original ATA formula [1] includes 10% of aircraft cost less engines and 40% of the engines cost for the initial spares stock).

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

Where:

L_d= depreciation life of aircraft [yr].

The depreciation life depends on the individual airline policy, the world economic and competitive condition as the airplane is maintained in a fully airworthy condition throughout its life and on the technologies on board.
As refer to IATA [13] generally aircraft assets are depreciated over 15 to 25 years with residual values of between 0 to 20 percent. The straight-line method of depreciation is the most commonly used. Small changes in useful economic life and residual value estimates can have a significant impact on the profit or loss in a period.

Airline	Aircraft/Fleet Type	Useful life (UL)	Residual Value (RV)	Depreciation Rate (DR = (100%-RV)/UL)
Air Astana	Flight equipment	10-20 years	-	5%-10%
	Rotable spare parts	5-10 years	-	10%-20%
Air China	Core parts	15-30 years	5%	3%-6%
	Airframe and cabin – refurbishment	5-12 years	-	8%-20%
	Overhaul of engine	2-15 years	-	7%-50%
	Rotable parts	3-15 years	-	7%-33%
Air France-KLM Group	Not specified	20-25 years	-	4%-5%
Cathay Pacific	Passenger	20 years	10%	5%
	Freighter	20-27 years	10%-20%	3%-5%
	Aircraft product	5-10 years	-	10%-20%
	Freighters converted from passengers	10 years	-	10%
EasyJet	Aircraft	23 years	-	4%
	Aircraft spares	14 years	-	7%
Emirates Group	New	15 years	10%	6%
	Used	5 years	10%-20%	16%-18%
	Engines and parts	5-15 years	0%-10%	6%-20%
Kenya Airways	Boeing 787, 777, 737-300, 737-700	17 years	-	6%
	Boeing 767*	3 years	-	33%
	Simulator	20 years	-	5%
Korean Airlines	Aircraft fuselage	6-15 years	-	7%-17%
	Aircraft engines and parts	15 years	-	7%
Lufthansa Group	New commercial	20 years	5%	5%

Figure 72 – Typical depreciation rate information for different aircraft types [13]

5.5.1. Depreciation CER Update

As for the depreciation equation, this compared to the NASA equation [2] has been partly revised and updated in order to make the model more flexible.

In fact, the fixed multiplicative coefficients (1.1 and 0.3) that were going to consider spare parts have been replaced by adaptive coefficients that are obtained precisely on the basis of the percentage of spare parts for the various terms. In addition, to ensure even greater flexibility, the term linked to avionics has been separated from that of the airframe. In this way, in the new equation appear separately all the items that undergo a depreciation within the aircraft with their relative spare parts.

$$DOC_D = \frac{(1 + AF_{spf})\left(\frac{C_{AF}}{W_{GTO}}\right) + (1 + AV_{spf})\left(\frac{C_{AV}}{W_{GTO}}\right) + (1 + TJ_{spf})\left(\frac{C_{TJ}}{W_{GTO}}\right)}{0.725\,(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) M \left(\frac{V_B}{V_{CR}}\right) U\,(L_d)}$$

Where:

AFspf = Airframe spare parts factor [%];

AVspf = Avionics spare parts factor [%];

TJspf = Turbojet spare parts factor [%];

These coefficients as suggested by the reference [3] are respectively equal to 0.1, 0.1 and 0.5

6. Study Case

In this chapter will be presented the study case and the estimate of operating costs related to the Green Concorde [7]. They will then be seen in the first step the inputs provided within a calculation tool developed in MATLAB for the calculation of direct operating costs.
The assumptions used to provide certain values within the model will also be explained.
Following this presentation then will be commented on the results obtained and finally with the purpose of validating this model, these values will be compared with both calculations effected with NASA model [2] of origin and both with reference values in the literature.
Finally, further comparative simulations will be presented to evaluate in quantitative terms the influence of the change in fuel cost (inside the DOC) compared to the factors that modify the latter and an estimation of total operating costs (TOC) for estimate the ticket price.

6.1. Input parameters: Aircraft, Mission, Economical and other parameters

It is of paramount importance to begin by presenting the input data that will be used as input values within the cost estimation model. These data will refer to:

- Details of the aircraft under consideration;
- Mission carried out data;
- Economical and miscellaneous data and parameters.

Most of the data will be found in the literature. In particular, the data concerning the aeroplane under consideration and the mission carried out will be taken within the reference [7]. Other data will be estimated through some references.

6.1.1. Aircraft data

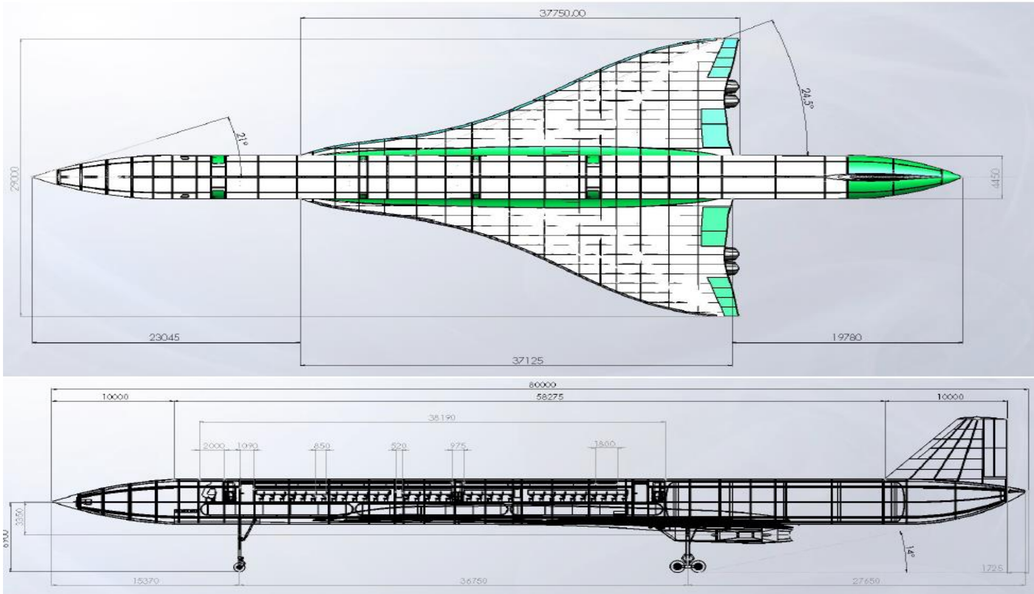


Figure 74 – Plant and lateral view with dimensions of Green Concorde [7]

AIRCRAFT DATA			
Number of installed engine	N_tj	-	4
Thrust per turbojet	T_tj	N	198550
Maximum thrust to weight ratio at take-off	T_Wgto	-	0,19
Airframe and subsystem weight	W_af	kg	90896
Avionics equipment weight	W_av	kg	590
Installed engine weight	W_tj	kg	15000
Fuel weight	W_ft	kg	24780
Payload weight	W_pl	kg	24750
Gross take-off weight	W_gto	kg	156016

Table 7 – Aircraft Input Data

Wing weight	17696.17 kg
Tail weight	1769.67 kg
Fuselage weight	25870.91 kg
Installed engine weight	15000 kg
Gear weight	6607.58 kg
Total empty weight	106590.30 kg
Fuel Weight	23600 kg
Payload	24750 kg
Take off weight	154836 kg

FCS	3670.88 kg
Hydraulic system	1468.3 kg
EPS	7341.75 kg
Fuel system	2936.7 kg
Air conditioning	11746.81 kg
Avionic system	4405.05 kg
Engine system	2202.53 kg
Furnishing system	5873.4 kg

Lift coefficient take off	0.69
Profile drag coefficient	0.03
Glide ratio in take off configuration	8.67
Climb gradient (≥ 0.024 for FAA)	0.03
Thrust to weight ratio	0.19
Thrust per engine [kg]	18992
Thrust to weight ratio	0.52

Figure 73 – Other Green Concorde Characteristics [7]

The first set of Input data in the new reference model for the calculation of DOC refers to the data for the aircraft under consideration. In this case, the aircraft under consideration are the Green Concorde [7] from which all input values required by the calculation model were taken. Specifically, as you can see in the table (xx) have been taken as values:

- 4 turbofan engines with low by-pass ratio (in order to partially reduce consumption) and equipped with afterburner capable of delivering a thrust of nearly 200 kN for each unit to be able to meet the demand for thrusts during all phases of the mission.

- A thrust to take-off weight ratio of 0.19 obtained through ASTRID software during the preliminary design phase that can reach a maximum value of 0.52 (value obtained by matching chart that reports the values of T/W on W/S in order to be able to select a minimum size T/W value for all phases of the mission).

- The values of the airframe weights, of the installed engines and of the avionics were inserted as a value output from the ASTRID software and compared at a later time with the values obtained from the CAD.
- The value of the fuel weight was entered on the basis of the results obtained from the ASTRID software. In this weight in addition to the fuel normally used for the mission is also included a fraction of fuel lost due to the phenomenon of Boil-off (5%) to which liquid hydrogen is subject and another fraction of fuel used as a reserve (6%) as required by current legislation.
- The value of payload weight has been inserted not only on the provisions of the ASTRID software but also on the provisions of CS25. In this case the payload was obtained through the formula:

$$W_{pl}\ [kg] = \left(W_{pax} * N_{pax}\right) + W_{cargo}$$

  This weight was obtained from the product of the number of Npax passengers multiplied by the average Wpax weight of 105 kg which includes the average passenger weight (85 kg) and the average baggage weight per passenger (20 kg). In addition to the weight due to passengers and luggage, an extra loading cargo has been introduced

- The final obtainable value for the maximum take-off weight has been obtained with the following formula which adds up the previously mentioned weight items:

$$W_{GTO}\ [kg] = W_{af} + W_{av} + W_{tj} + W_{ft} + W_{pl}$$

6.1.2. Mission data

The second set of inputs concerns mission data. All the Data present here are essentially related to the mission carried out by the reference aircraft (Table7).

MISSION DATA			
Operative Range	Rt	km	8000
Flight time	Tf	h	4.2254
Cruise Mach	M	-	2.76
Lift to drag Ratio	L/D	-	18
Average Cruise altitude	H	m	18175
Reserve Fuel fraction	K_r	%	0.06
Boil-off Fuel Fraction	K_bo	%	0.05
Block Velocity	V_b	km/bhr	1787.5
Cruise velocity	V_cr	km/h	2931.5

Table 8 – Mission Input Data

MISSION PHASE	DURATION		ALTITUDE (phase start)		ALTITUDE (phase end)		SPEED	
	Ore	Minuti	ft	metri	ft	metri	m/s	km/h
Pre - flight checks	0.0833	5	0	0	0	0	0	0
Engine start-up	0.0333	2	0	0	0	0	0	0
Taxi out	0.25	15	0	0	0	0	0	0
Take off (run)	0.01667	1	0	0	0	0	140	504
Take off (manoeuvre)	0.000464	0.02782	0	0	65.6168	20	140	504
Afterburner - On	Start time [%]:	1	-	-	-	-	-	-
Subsonic climb	0.025	1.5007	65.6168	20	16404.2	5000	189	680
Flaps retraction	Start time [%]:	30	-	-	-	-	-	-
Landing gear retraction	Start time [%]:	10	-	-	-	-	-	-
Subsonic cruise	0.17	10	16404.2	5000	30200.13	9205	261	940
Afterburner - Off	Start time [%]:	3	-	-	-	-	-	-
Supersonic climb	0.07874	4.724	30200.13	9205	60695.54	18500	489	1760
Afterburner - Off	Start time [%]:	99	-	-	-	-	-	-
Afterburner - On	Start time [%]:	45	-	-	-	-	-	-
Supersonic cruise	2.42	145	60695.54	18500	58566.27	17851	732	2635
Descent	0.8325	49.9473	58566.27	17851	2296.588	700	438	1577
Landing gear extension	Start time [%]:	95	-	-	-	-	-	-
Flaps extension	Start time [%]:	90	-	-	-	-	-	-
Holding	0.08333	5	2296.588	700	2194.882	669	108	389
Approach	0.03636	2.1817	2194.882	669	656.168	200	110	396
Missed approach	0.50003	30.0017	656.168	200	2132.546	650	113	407
Landing (manoeuvre)	0.09563	5.738	2132.546	650	6.562	2	112	403
Landing (run)	0.1667	10	6.562	2	0	0	55	198
Taxi in	0.25	15	0	0	0	0	14	50
Engine shutdown	0.01667	1	0	0	0	0	0	0

Table 9 – Green Concorde mission detail [7]

All values present in this section are taken from the reference project [7].
All these values have been processed using specific software (Astos and Astrid) to be able to best simulate the phases of the typical mission carried out by Green Concorde [7].
In order to provide further details on the values used for the calculation, it shall be specified that:

- Flight time has been set on the basis of the values given by reference [7] and shown in table (8) from take-off to landing;
- The Range, Cruise Mach and aerodynamic efficiency used in the calculation are those given by the reference [7] to accomplish the chosen mission (intercontinental flight London-New York).

- The value of the cruising altitude used was taken as the average value between the beginning altitude (18500 m) and the end altitude of the supersonic cruise (17850 m).
- The value of the spare fuel fraction used was equal to that of the reference, which in turn refers to the legislation in force.
- The fuel fraction value to account for the Boil-off phenomenon has been placed equal to that given by the reference.
- The value inherent to the block speed comes from the calculation of the block time. This refers to the time between the closing of the doors of the aeroplane preceding the take-off phase and the opening of the doors following the landing phase.

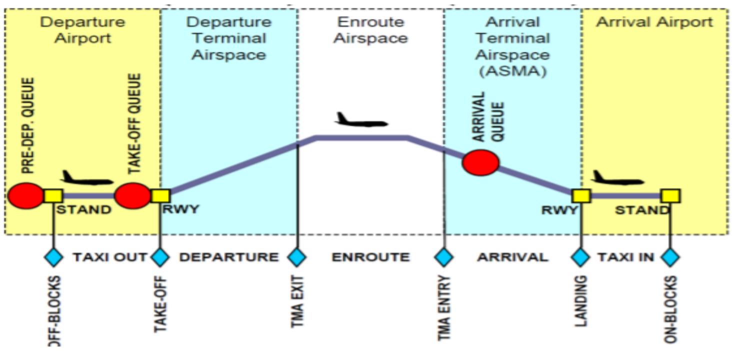


Figure 75 – Block-to-Block flight time [46]

Through the reference [3] it is possible to estimate theBlock time Tb come:

$$Tb\,[bhr] = Tf + 0.25$$

Where the Tf is the flight time expressed in hours. This value describes the block speed expression simply by the range ratio RT on Block time Tb:

$$Vb\left[\frac{km}{bhr}\right] = \frac{Rt}{Tb}$$

The cruising speed expressed in km/h is calculated as a function of the cruising Mach and the speed of sound at cruising altitude.

$$Vcr\left[\frac{km}{hr}\right] = 3.6 * M * \sqrt{\gamma\, R_a\, T_{cr}}$$

Where the coefficient of adiabatic expansion γ for a diatomic gas such as air is 1.4, the air constant Ra given by the ratio R0/m_a is 287 while the absolute temperature at cruising altitude Tcr taking as a reference the values of the standard atmosphere is 216.65 K

6.1.3. Productive and Operating Scenario data

The last set of inputs are related to the Economical and Operating scenario. In this case economic data that are useful for the cost estimation such as depreciation life, load factor, insurance annual rate, fuel cost per weight units or cost price index are reported (table 9).

OTHER INPUT DATA			
Insurance rate	IR	%	0,025
Consumer price index from 1967 to 2021	CPI_1967	%	7,95
Consumer price index from 1972 to 2021	cPI_1972	%	6,35
Aircraft Utilization	U	Bhr/yr	1750
Depreciation life	L_d	yr	15
Load Factor	Lf	%	0,7
Average labor rate hourly salary	R_l	$/hr	32,19
Hours between engene overhaul	TBO	hr	5000
Maintenance material ratio for turbojet engine	K_mtj	-	1,7
Maintenance labor ratio for turbojet engine	K_ltj	-	1,7
Fuel cost	Cf	$/kg	4,5
Airframe spare part factor	af_spf	%	0,1
Avionics spare part factor	av_spf	%	0,1
Turbojet spare part factor	tj_spf	%	0,5
Turbojet Spare Part Price Factor	tj_sppf	-	1,1

Table 10 – Economical and miscellaneous Input Data

As far as the values used here as input are concerned, it can be said that:

- As already reported in the NASA model [2] at the beginning of the operating life, the insurance rate of an aircraft is expected to be 5% of initial value of the aircraft the first years to fall to 2% after few years. This method suggests in the absence of data to use an IR equal to just 2% of the initial cost. However, this value is best suited to the case in analysis from the NASA model [2] for HST where only 10 years of operation are expected. In this case considering an operating scenario of the aircraft of 15 years, it was preferred to use an arithmetic average that estimated with greater precision IR leading therefore to the choice of an IR value of 2.5%.

- The Consumer Price Index (CPI) is an essential conversion factor for the normalisation of costs compared to the fiscal year under consideration. Since part of the work carried out by NASA in 1973 [2] refers to the ATA model [1] with market values referring to 1967 in order to succeed in normalizing the corresponding reference values, two normalization coefficients have been introduced, one of the values of 7.95 (which keeps track of inflation from January 1967 to January 2021) and another of the value of 6.35 (which keeps track of inflation from January 1973 to January 2021).

- The value of aircraft utilization is the number of Block hours performed in a whole calendar year. This value is also indicative of the flight numbers that the vehicle is able to perform in a year. In this case NASA [2] provides reference values ranging from 3000 to 4500 hours in a year. Most recent values reported by MIT [44] choosing a value of 4000 hours of use of the aircraft in one year (value still within the range proposed by NASA [2]). Anyway, this value is very high for the study case and can be considered suitable especially for subsonic aircraft as for blocking time the required maintenance hours vary between 1 and 2 hours. In the case of supersonic aircraft due to the stresses that the latter undergo during their mission (think for example of the stresses brought by the sonic boom) the hours of maintenance required for block hours are much greater (in the agreement these even reached 20 hours of maintenance per hour of flight). For this activity we wanted to refer to the maintenance hours used for supersonic military aircraft in which the hours of maintenance vary from 3.5 to 4.5 hours of maintenance per hour of flight. Finally choosing a value of 4 hours of maintenance trusting in the technological progress that has been made over the years, obtained about 1750 block hours of utilization in one years (391 flight).

- The value of the depreciation life is closely linked to the policy adopted by the airline and also generally by the use of particular technologies on board the aircraft. The NASA model [2] suggests for HST a value of 10 years with a residual value of 0% while 15 years for subsonic aircraft. Current market values suggest for a subsonic jet a depreciation life from 15 to 25 years with a residual value ranging from 0 to 20% of the initial price. Wanting to stay in line with the current data but without going too far from the reference and it was therefore chosen to use for the case in question a depreciation life value of 15 years and a residual value of 0%.

- The load factor, is the percentage of payload assumed to be present in each flight. In this case, the NASA model [2] suggests a value of 60% for HST. Referring instead to what was reported by IATA [51] with post-pandemic market values, it was decided to assume a load factor value of 70%.

- The wage of maintenance worker is inserted by updating through the appropriate consumer price index of 1973 the value of 4$ / hr proposed by NASA [2]. This normalization of the price to bring this cost to a value of $ 32 / hr resulting almost perfectly in line with the current wages reported by IATA [31].

- The hours (or time) between overhauls TBO are the manufacturer's recommended number of running hours or calendar time before an aircraft engine or other component requires overhaul. As suggested by Roskam [3], for a subsonic jet this value is included from 3000 (old jet engine generation) to 6000h (new engine generation), for a second generation of supersonic aircraft 5000 is good value due to represent the high wear rate

- The maintenance material/labor rate describing peculiar aspects of maintenance of turbojet have been estimated following indications reported in NASA methodology [2]. They are necessary to evaluate the cost of the maintenance of engines. The value suggests by NASA methodology [2] are evaluated considering the data from ATA [1] (for subsonic and sonic aircrafts). Those coefficients compare the maintenance required from hypersonic engines with an equivalent subsonic engine. For this work, is more properly used the value suggested by ATA of 1.7 for those rates.

- The cost of fuel per kg consider in this job is refer to the value of 4.9 $2019/kg present in the reference [8]. Liquid hydrogen shall be considered obtained from 60% electricity from grid and 40% from renewables assuming in current scenario and US as production country. With the previous data a value of 5 $2021/kg was selected for the study case.

Electricity from grid (%)	Electricity from renewables (%)	Liquid hydrogen total cost [€2019/kg]		
		Current scenario (2020)	Near-future scenario (2030)	Long-term future scenario (2050)
100	0	6.8	5.1	4.4
90	10	6.3	4.7	4.1
80	20	5.9	4.4	3.7
70	30	5.4	4.0	3.4
60	40	4.9	3.6	3.0
50	50	4.4	3.3	2.7
40	60	4.0	2.9	2.4
30	**70**	**3.5**	**2.5**	**2.0**
20	80	3.0	2.1	1.7
10	90	2.5	1.8	1.4
0	100	2.1	1.4	1.0

Table 11 – Liquid hydrogen cost variation based on electricity source [8]

- Finally, coefficients related to spare parts have been inserted for Airframe, avionics and engine. These values are presented within NASA model [2] in the cost of depreciation of the aircraft assuming values of 10% for airframe and avionics and 40% for the engine. The latter value has been revised by taking into account the current market benchmark to a value of 50 % (as suggested by the [3] benchmark). This further increase in costs was also reflected in the tj_sppf in a factor which takes into account the cost of the replacement parts of the engine within the maintenance parts (a 10% increase in engine spare parts costs was assumed).

At this point all the data set useful to be able to perform the calculation with the updated model has been executed in the next paragraph will be analyzed the results obtained from the new model of equations for estimation of DOC.

6.2. Output Value: Acquisition Cost and DOC

In this paragraph will be seen and analysed what are the results obtained through the MATLAB script containing the new model of equations for the estimation of direct operating costs.
Before we begin, it should be noted that the script was developed from the updated equations seen in Chapter 5. These equations derived from the NASA model [2] present as a unit of measurement the cost in $ per ton thousand. Given the interest in comparing the values derived from the estimate with references in the literature and with other models, it was decided to develop the MATLAB script by reporting the equations already properly converted so that they returned values in $/bhr. It is important to clarify how this conversion is the result of an inverse operation compared to what NASA did with its reference (ATA [1]).
Finally, it should be specified that this conversion has not been carried out for the CREW cost estimation and maintenance equation as they are already in the correct unit of measurement.

$$\$/ton - mille \rightarrow \$/bhr = (LF) * \left(\frac{W_{PL}}{2000}\right) * 680 * M * \left(\frac{V_B}{V_{CR}}\right)$$

In addition, to further facilitate the understanding of these values in an absolute sense and to evaluate their internal distribution, they were subsequently reworked to provide output values expressed first in $/flight and then in %.

$$\$/bhr \rightarrow \$/flight = \frac{R_t}{680 * M * \left(\frac{V_B}{V_{CR}}\right)}$$

6.2.1. Acquisition Cost

As seen in Chapter 4 and Chapter 5, within the NASA model [2] there are reports that can estimate the total cost of the aircraft and some of its subsystems and specifically: the airframe, avionics and engines.
These relationships are essentially based on the dimensional characteristics of the aircraft and its performance.
However, considering that these relations were developed in September 1973, it is logical to consider that the amounts returned should be updated accordingly to the tax year in question. In our case, therefore, CPI_1972 was used to obtain consistent values (31 December 1972). However, from a first comparison with market values it was immediately understood that this transaction was not sufficient to obtain consistent values because the estimate of costs returned values too low, especially with regard to the cost of avionics and the engine. When NASA method [2] was realized, the avionics had only a marginal role inside the aircrafts. Nowadays the avionics is a fundamental subsystem in the aircraft. The same argument can be faced for the engines as the latter have also been enriched with electronics bringing them to technological levels significantly higher than the previous generations taken in reference to the NASA model [2]. Nowadays the sum of these two subsystems can

reach up to 50% of the cost of acquiring the entire aircraft. Reason why additional cost escalation factor of the specific value of:

- Avionics CEF: 2
- Turbojet CEF: 4

At this point it is possible to observe the results obtained:

```
AIRCRAFT COST, AIRFRAME+SUBSYSTEM,AVIONICS AND ENGINE

C_af airframe and subsystem cost [$] :      1.2189e+08

C_tj turbojet engine cost [$] :             8.6116e+07

C_av avionics cost [$] :                    2.5892e+07

C_A aircraf total cost [$] :                 2.339e+08
```

Figure 76 – Study case - Aircraft and subsystems Cost

It is important to underline that this cost turns out to be an average static cost which can be representative of a production started. However, it is in no way representative of the dynamic cost that the aircraft can have throughout the production period. As has been described in Chapter 2, the cost of production of an aircraft is closely linked to the units produced by that aircraft. In fact, by varying the number of units to be produced, the cost per unit will tend to decrease due to numerous factors such as the reduction of costs due to the optimization of the production process (learning curve), access to greater market discounts on the purchase of raw materials, the redistribution of fixed expenses (i.e., design cost) on a greater number of units, etc.

Some comparisons and market research were carried out to verify the effectiveness of the results obtained. It was immediately observed that prices were in line with current market values for wide-body aircraft. In detail, the cost of avionics on modern civil aircraft is currently about M$ 20 [47] while as for the engine, a turbofan of the latest generation always as reported by the reported [48] (depending on performance), can cost up to 40 M$ (as in the case of the new GE9X).
A final check on these values was made through the comparison with the real cost values of another historical reference aircraft or with the acquisition costs of the Concorde.
At the end of 1977 the cost of acquiring the Concorde was £23 million. [55] value that currently properly updated and converted corresponds to about 205 M$. The final value for the Green Concorde of 233.9 M$ obtained with the new estimation model is fully comparable with the updated one of the Concorde taking into account the different levels of technology on board, the different performance but above all the different dimensions of the two aircraft (the Green Concorde [7] is considerably larger than the Concorde also by virtue of having to accommodate the large tanks necessary to contain liquid hydrogen as fuel and a greater number of passengers on board).
A further comparison of the data is done with the cost estimation model proposed by NASA [2]. In this case it is possible to notice from the beginning that the final acquisition cost proposed by NASA [2] is much lower than that obtained with the

new model by about 33%. This value is also far from the price of Concorde discounted on the market.

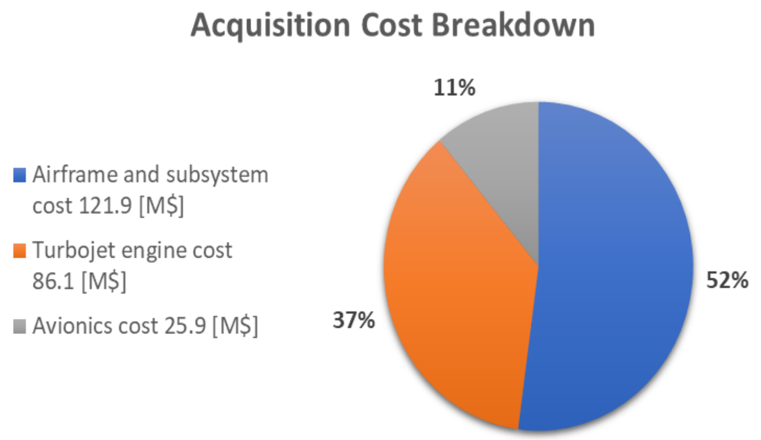


Figure 77 – Aircraft acquisition cost breakdown

6.2.2. DOC Cost Estimate

In this subsection we will analyse the direct operating costs obtained through the new estimation model. This will be immediately compared with the model of NASA [2] in order to evaluate the variations between the two will be compared with other reference values from other models and market values.

DIRECT OPERATIVE COST PER BLOCK HOURS ESTIMATE		
[$/bhr]	NEW model	NASA model
DOC_fuel	12162	12162
DOC_crew	1727	2032
DOC_insurance	1567	1048
DOC_depreciation	5212	3188
DOC_M_AF_L	231,89	257
DOC_M_AF_M	1198	271
DOC_M_TJ_L	117	34
DOC_M_TJ_M	3676	198
DOC_Maintenance	5223	760
DOC per Block Hours	25891	19190

Table 12 – Study case - Direct Operative Cost per block hours estimate

The table (11) shows the values of direct operating costs expressed in $/bhr obtained through the use of the updated calculation model and model from NASA [2].

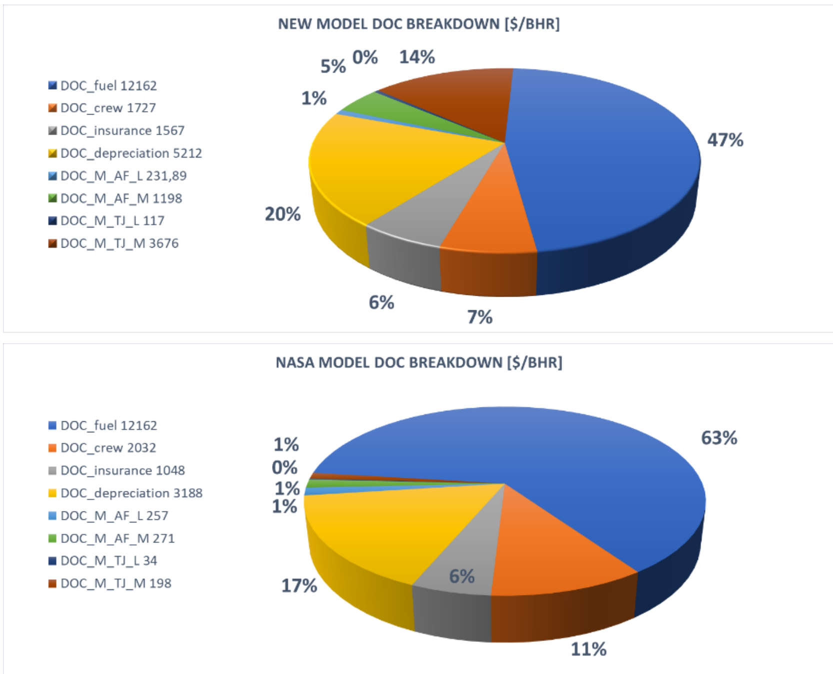


Figure 78 – DOC breakdown comparison between new model and NASA model

It is very interesting to analysed what are the typical aspects and the differences highlighted by the results also in the face of what is shown in Figures 78:

- First of all, it is easy to observe that inside the DOC the majority voice is that linked to fuel. This represents almost half of the DOC in the new estimation model and almost 75% in the NASA model [2]. In this case, of course, this item is largely linked to the cost per kg of fuel.

- The breakdown of DOC values into possible future scenarios with different fuel costs will be analysed below.

- In both models, the crew cost is an expense to be taken into account, even exceeding 10% of the DOC in the NASA model [2]. Assessing the difference between the values obtained between the two models, it is possible to see how the crew cost of the updated model is 15% lower than the NASA model [2]. The values obtained so far are both derived from the same reference. However, the value proposed by NASA [2] is a fixed value obtained from a numerical extrapolation of the values suggested by ATA [1]. The new method instead takes as reference the formula of departure proposed by ATA, this turns out to be more flexible because it returns a value in function of the maximum weight to the take-off of the aircraft. Again, the value obtained was then normalised to the tax year under consideration. From a comparison with the market values presented by IATA in 2019 in the case of wide-body subsonic aircraft [50] it seems that both solutions can be taken as a reference.

- One of the minor items in the DOC breakdown is certainly the cost of insurance. The difference between the values shown, however, is due to a different insurance coefficient chosen and a different cost of the aircraft and the different utilization value. In fact, if in the NASA [2] Insurance rate model was placed as 2% of the acquisition value of the aircraft, the value chosen in the updated model (2.5%) is the son of a mathematical average calculated on the basis of the variation in the insurance rate compared to the years of operation of the aircraft. In addition, as highlighted in the previous paragraph, the cost of the aircraft in the new model is higher than that proposed by NASA and more in line with what are the current market values, and good average value of utilization is far less than 4000 block hours per year how NASA suggested.

- Also, with regard to the cost of depreciation this stands at different percentages between the two models within the DOC. Again, as seen for the cost related to insurance, also here it is the greater cost of the means in the new model to drive more the difference between the values obtained compared to a more insignificant increase of the coefficients that take into account spare parts and the different utilization in the year.

- As far as maintenance costs are concerned, here it is possible to observe the very substantial difference between the two models both in terms of DOC allocation and in terms of absolute values. In the NASA [2] cost estimation model, the cost of maintenance was extremely low (less than 5% of DOC) while the values obtained with the updated model represent just less 20% of DOC. These values are much more in line with the actual maintenance values required for SST. All the cost estimation models referred to are pre-dated to the entry into service of Concorde.

Costing-Method Comparison for B-707 and US SST: Cost per Block Hour for Aircraft Labor

Method	Domestic 1500-mile basis, dollars		International 3000-mile basis, dollars	
	B-707	US SST	B-707	US SST
RAC	32	132	26	108
FAA 66	53	85	52	83
ORI	34	63	33	55
PRC	34	54	33	53
LAC	51	142	43	118
ATA 66	36	53	37	55
Boeing	32	93	24	72

Costing-Method Comparison for B-707 and US SST: Cost per Block Hour for Engine Labor

Method	Domestic 1500-mile basis, dollars		International 3000-mile basis, dollars	
	B-707	US SST	B-707	US SST
RAC	25	72	25	72
FAA 66	21	55	21	54
ORI	35	82	34	81
PRC	22	56	21	55
LAC	13	30	12	28
ATA 66 (proposed)	25	49	26	51
Boeing	21	70	17	73

Costing-Method Comparison for B-707 and US SST: Cost per Block Hour for Aircraft Material

Method	Domestic 1500-mile basis, dollars		International 3000-mile basis, dollars	
	B-707	US SST	B-707	US SST
RAC	26	117	21	93
FAA 66	28	150	27	147
ORI	59	185	58	182
PRC	23	128	23	125
LAC	34	275	29	242
ATA 66	32	162	32	169
Boeing	32	118	23	86

Costing-Method Comparison for B-707 and US SST: Cost per Block Hour for Engine Material

Method	Domestic 1500-mile basis, dollars		International 3000-mile basis, dollars	
	B-707	US SST	B-707	US SST
RAC	48	262	17	259
FAA 66	56	289	54	283
ORI	59	161	58	157
PRC	46	277	45	272
LAC	48	248	45	238
ATA 66 (proposed)	48	214	49	223
Boeing	32	183	27	191

Figure 79 – Costing-Method Comparison for B-707 and US-SST [49]

As it is historically known, the economic failure of the Concorde program was closely linked to an erroneous estimation of maintenance costs found to be extremely burdensome.

Today engine maintenance governs this cost item as also illustrated by IATA [50].

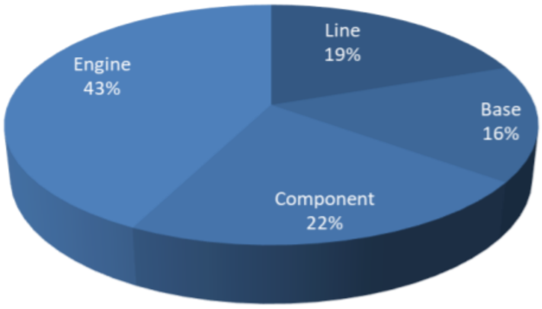


Figure 80 – Direct Maintenance Cost Breakdown by segment [50]

The big difference in this case compared to the original NASA model is mainly due to the increase in engine costs which consequently had a significant impact on maintenance costs. In fact, using the same discounting factors on the market within the cost in the NASA model, one could observe in general an increase in costs due to the material both for the part of the materials due to the airframe but in a much more significant way for the cost of the materials due to the engines ($/bhr 790.35), giving an explanation to the wide range that separates the two models for this cost item.

6.3. Comparison with other aircraft, and variation of DOC as fuel cost changes.

IATA report [50] show the fixed and variable operating cost per block hours for the passenger airlines. The average operating costs are about $/bhr 4352 (for all type of aircraft).
As is possible to see in the figure (82) belove by reference [50]:

	1	2	3	4	5	6	7	8	9	10	11
Aircraft Category	Cost per Block Hour										Block Hours
	Fuel and Oil	Maintenance	Crew	Total Variable	Depreciation	Rentals	Insurance	Other	Total Fixed	Total	
Wide-body more than 300 seats	$5,411	$1,331	$2,356	$9,097	$845	$406	$4	$1	$1,254	$10,351	220,210
Wide-body 300 seats and below	$4,080	$1,289	$1,857	$7,227	$685	$366	$4	$4	$1,058	$8,285	2,091,230
Narrow-body more than 160 seats	$2,054	$718	$1,152	$3,925	$355	$217	$3	$7	$582	$4,506	3,991,243
Narrow-body 160 seats and below	$1,741	$737	$1,034	$3,512	$306	$215	$5	$7	$533	$4,045	9,267,585
RJ more than 60 seats	$115	$431	$444	$991	$131	$252	$1	$13	$397	$1,388	3,565,900
RJ 60 seats and below	$92	$479	$470	$1,041	$58	$227	$1	$7	$293	$1,334	1,326,851
Turboprop more than 60 seats	$0	$880	$360	$1,241	$439	$103	$0	$2	$544	$1,785	116,701
All Aircraft	**$1,681**	**$727**	**$1,012**	**$3,420**	**$314**	**$239**	**$4**	**$7**	**$564**	**$3,985**	**20,579,720**

Figure 81 - IATA Part 121 – Operating and Fixed Costs per Block Hours [50]

The total operating costs per block hour for a subsonic jet wide-body airplane with less of 300 seats is 8.285 $/bhr ($F.Y. 2021/bhr 9250). This cost is significantly lower than what has been estimated for our reference aircraft ($F.Y. 2021/bhr 24929). Is easily to imagine that the operating costs of a subsonic aircraft are lower than for an SST or HST.

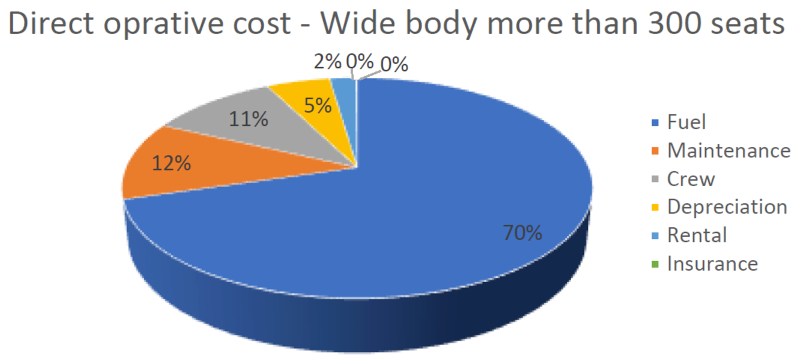


Figure 82 – Wide-Body DOC [51]

In both cases, the most relevant cost item is the fuel cost (as can see in figure 83). However already reducing the cost of the fuel bringing it to values similar to those of the hydrocarbons it can be noted as the values tend gradually to align themselves while maintaining a certain gap (using a fuel cost of $1.5/kg results in a DOC value of $16415 - about 77% more than the DOC of a subsonic aircraft.

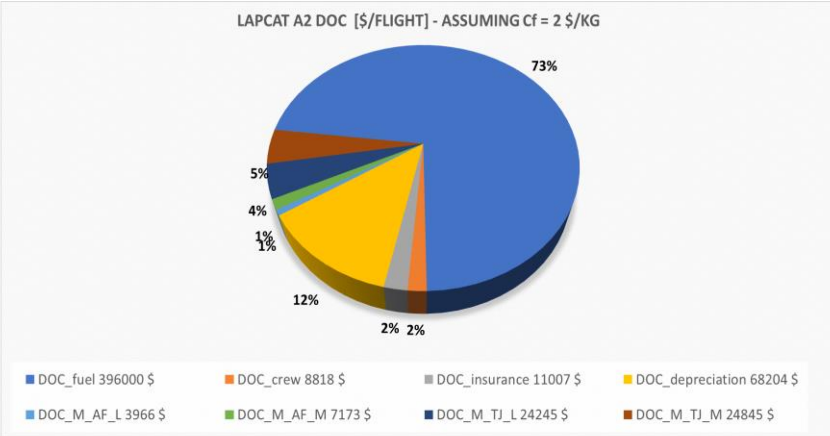


Figure 84 – LAPCAT A2 DOC assuming 2$/kg as fuel cost

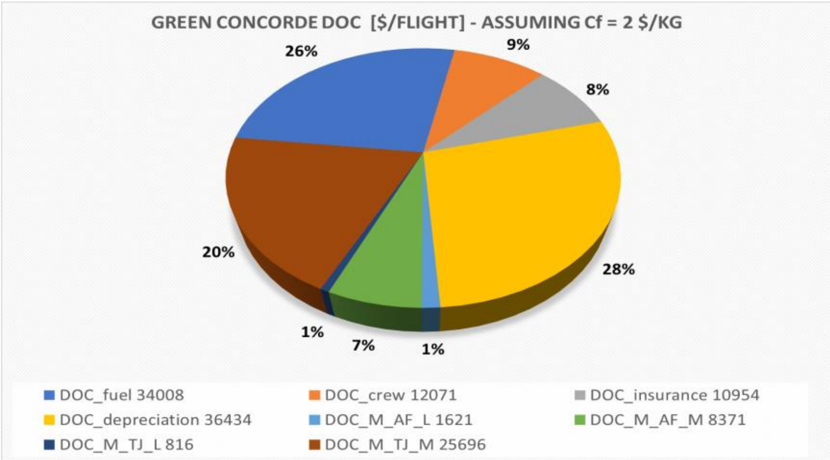


Figure 83 – GREEN CONCORDE DOC assuming 2$/kg as fuel cost

DIRECT OPERATIVE COST PER FLIGHT		
[$/flight]	GREEN CONCORDE	LAPCAT A2
DOC_fuel	34008	396000
DOC_crew	12071	8818
DOC_insurance	10954	11007
DOC_depreciation	36434	68204
DOC_M_AF_L	1621	3966
DOC_M_AF_M	8371	7173
DOC_M_TJ_L	816	24245
DOC_M_TJ_M	25696	24845
DOC_Maintenance	36504	60228
DOC	129971	544257

Table 13 – Direct operative Cost per Flight comparison between Green Concorde and LAPCAT A2

Taking instead as reference the values reported in [8], assessing the costs per flight compared to a hypersonic aircraft like the LAPCAT A2 is possible see the wide difference that separates the two cases. Obviously, such a comparison serves only from the qualitative point of view (as well as that made with subsonic aircraft) to understand the order of magnitude that they go to compare. The values obtained in fact often refer to very different types of aircraft both according to the different operating scenarios that will face each of these categories but above all due to the obvious differences in performance that these are able to guarantee.

Ultimately, the impact on the DOC of the change in fuel prices is assessed.
As widely described in the previous chapters, this is linked to several aspects such as:

- region of production,
- production scenario
- energy sources used for production.

If the cost per unit of weight of fuel increases the fuel DOC follow the same trends.
Generally, the cost of fuel tends to decreases if the production rate grows.
Nowadays, the difference between the fuel price per kilogram between the production region is evident. In fact, the European cost of LH2 is about the twice than the American end four-time respect Arabian Country. That's because change the cost of production energy between different countries. It is interesting to see that in the future productive scenarios, the difference of fuel costs between EU and US is less. Furthermore, in the "Future" scenarios, the DOC of fuel produced in USA and Europe and the total DOC tend to be the same.
As referred in [8], considered the production scenario in 2050 in the US and obtained from 30% grid and 70% from renewables, the fuel cost is 2.2 $ F.Y. 2021/kg.
Through this value the DOC became:

DIRECT OPERATIVE COST PER BLOCK HOURS ESTIMATE	
[$/bhr]	NEW model CF=2.2
DOC_fuel	5351
DOC_crew	1727
DOC_insurance	1567
DOC_depreciation	5212
DOC_M_AF_L	232
DOC_M_AF_M	1198
DOC_M_TJ_L	117
DOC_M_TJ_M	3676
DOC_Maintenance	5222
DOC per Block Hours	19079

Table 14 - Direct operative Cost per Block Hours assuming 2,2 $/kg as fuel cost

It is very interesting to note that supposed this as cost value of fuel, the DOC of fuel have the same order of magnitude of maintenance operative cost and depreciation (28% for all DOC cost voice).

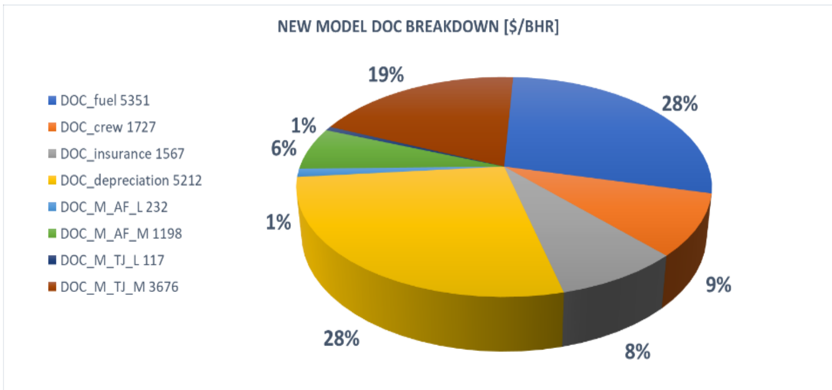


Figure 85 – Green Concorde DOC breakdown assuming 2,2 $/kg as fuel cost

6.4. IOC and Ticket price estimation

As defined in the introductory chapter to be able to estimate all operating costs and it is necessary to estimate in addition to direct operating costs also indirect operating costs.
The estimation of indirect operating costs is extremely complex. In fact, the IOC do not depend on factors properly related to the design of the aircraft but more on external economic factors and marketing strategies. In general, is can expect that the indirect operating costs of a liquid hydrogen powered supersonic aircraft are higher than those of a conventional aircraft lane.
In some cases, IOC can be estimated as a simple percentage of DOC. Indirect operating costs are between 15 % and 50 % of the total operating costs according to the reference [6].

DIRECT OPERATIVE COST PER FLIGHT	
[$/flight]	GREEN CONCORDE
DOC_fuel	85020
DOC_crew	12071
DOC_insurance	10954
DOC_depreciation	36434
DOC_M_AF_L	1621
DOC_M_AF_M	8371
DOC_M_TJ_L	816
DOC_M_TJ_M	25696
DOC_Maintenance	36503
DOC	180982

Table 15 – Green Concorde DOC per flight

In this case, using as a basis of direct operating cost what obtained from the study case and placing as IOC 45% of TOC we get:

$$TOC\ [\$/flight] = \ DOC + IOC = DOC + 0.45 * TOC = 329058$$

$$DOC \left[\frac{\$}{flight}\right] = \ 180982\ ;\ \ IOC \left[\frac{\$}{flight}\right] = \ 148076$$

Through this value in the end, it is possible to estimate the current minimum (static) cost of the ticket. Total operative cost are increases by 10 % to consider revenues which airline companies apply on the ticket price:

$$Ticket\ Price\ [\$] = \frac{TOC * 1.1}{N_{pax}} = 1828$$

This value is partly uncompetitive compared to those offered by low-cost companies that face the same route proposing an average ticket price in economy of about 400$, is instead highly competitive if you consider the costs related to the first class or business classes and in some cases compared to the price offered to travel on the same route in premium economy (i.e., Virgin Atlantic offers a price of about $1750). It is also important to consider that, in addition to the cost factor, the possibility of running these routes in about half the time should be considered very important, reaching shareable speed only with a few other vehicles in the world and above all doing it through an aircraft that is highly respectful of the environment where we live.

7. Software tools

In this chapter we will illustrate and comment on the MATLAB script created to be able to perform the case study calculations reported in the previous chapter. It should be noted that in addition to the use of MATLAB software, the use of Microsoft Excel has also been used to obtain graphs that are more editable than those obtained in the MATLAB environment.

7.1. MATLAB script development

The program chosen for the development of the calculations is MATLAB. Through this versatile software it was possible to create this first version of the script that contains all the information necessary to be able to calculate the direct operating costs using both the new cost estimation model and the one proposed by NASA [2] in 1973.

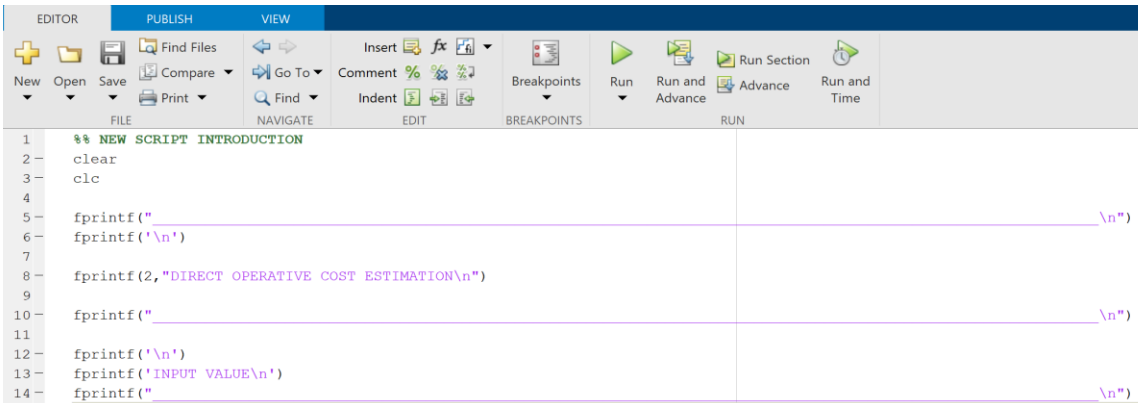


Figure 86 – MATLAB Script Editor view

The first lines of the code are useful to clean up the windows command and to report the title of the script. As you can see, the "fprintf" command has been widely used to be able to give a precise formatting and order to the values displayed within the windows command.

The script has been set up in 4 macro sections: introduction, input, output, graphs and data export to excel. In turn, the macro input section has been divided into three sections in which, as seen in the previous chapter, the parameters relating to:

- aircraft;

```
%% INPUT AIRCRAFT PARAMETERS

fprintf(2,'AIRCRAFT PARAMETERS\n')
fprintf('\n')

fprintf ("N_tj Number of installed engine :                    ")
N_tj= 4;
disp(N_tj)
fprintf('\n')

fprintf ("T_tj Thrust per turbojet [N] :                    ")
T_tj= 198550;
disp(T_tj)
fprintf('\n')

```

- mission;

```
%% INPUT MISSION PARAMETERS

fprintf(2,'MISSION PARAMETERS\n')
fprintf('\n')

fprintf ("Rt Range [km] :                                                           ")
Rt= 8000;
disp(Rt)
fprintf('\n')

fprintf ("Tf Flight time [h] :                                                     ")
Tf= 4.2254;
disp(Tf)
fprintf('\n')
```

- economic scenario and other parameters.

```
%% INPUT ECONOMICAL AND MISCELLANEUS PARAMETERS
fprintf(2,'OTHER PARAMETERS\n')
fprintf('\n')

CPI_1967_2021 = 7.95; % Consumer Price Index from 1967 to 2021
CPI_1972_2021 = 6.35; % Consumer Price Index from 1972 to 2021

fprintf("IR insurance rate [x100] :                                          "),
% NASA suggested IR = 2% (5% only first year)
IR = 0.025;
disp(IR)
fprintf('\n')

fprintf("U Aircraft Utilization [Bhr/yr] :                                    "),
% NASA suggested 3000-4500 Bhr/yr, while MIT 4000 Bhr/yr
U = 4000;
disp(U)
fprintf('\n')
```

Within some lines of code, suggestions have been inserted (text highlighted in green) in order to help the user in choosing the value inherent in the parameter to be inserted.

In addition to the input section, the output section macro has also been divided into four sections that show respectively:

- Aircraft acquisition cost CERs;

```
%% AIRCRAFT ACQUISITION COST CERS

fprintf (2,"AIRCRAFT COST, AIRFRAME+SUBSYSTEM,AVIONICS AND ENGINE \n")

TJAMPF = 4;   % Turbojet Market Actualized Price Factor %
AVAMPF = 2;   % Avionics Market Actualized Price Factor %
fprintf('\n')

fprintf ("C_af airframe and subsystem cost [$] :                                  ")
C_af = 855 *((W_af)^0.68) * (M^2) * CPI_1967_2021 ;
disp(C_af)
fprintf('\n')

fprintf ("C_tj turbojet engine cost [$] :                                          ")
C_tj = 6300 * ((N_tj)^-0.15) * ((T_tj)^-0.33) * T_Wgto * W_gto * CPI_1967_2021 * TJAMPF;
disp(C_tj)
fprintf('\n')
```

- DOC fuel, insurance, crew and depreciation CERs expressed in $/block hours

```
%% DOC CERS per block hours
fprintf (2,"DIRECT OPERATIVE COST PER BLOCK HOURS ESTIMATE\n")
fprintf('\n')

DOC_fuel = (1460*Cf*(W_ft/W_gto)*(1-K_r))/((Lf*(W_pl/W_gto)*Rt))*(Lf*(W_pl/2000)...
    *680*M*(V_b/V_cr));
fprintf ("DOC_fuel [$/bhr] :                                        ")
disp(DOC_fuel)
fprintf('\n')

DOC_crew = (0.05*((W_gto*2.205)/1000)+ 200)*CPI_1967_2021;
fprintf ("DOC_crew [$/bhr] :                                         ")
disp(DOC_crew)
fprintf('\n')

DOC_insurance = ((IR*(C_A/W_gto))/(0.725*Lf*(W_pl/W_gto)*M*U*(V_b/V_cr)))*...
    (Lf*(W_pl/2000)*680*M*(V_b/V_cr));
fprintf ("DOC_insurance [$/bhr] :                                    ")
disp(DOC_insurance)
fprintf('\n')

DOC_depreciation = (((1+af_spf)*(C_af/W_gto)) + ((1+av_spf)*(C_av/W_gto)) + ...
((1+tj_spf)*(C_tj/W_gto)))/(0.725*Lf*(W_pl/W_gto)*M*U*(V_b/V_cr)*L_d)*...
(Lf*(W_pl/2000)*680*M*(V_b/V_cr));
```

- DOC maintenance CERs expressed in $/block hours

```
%% DOC Maintenance CERS

DOC_M_AF_L = R_l * (3+((0.067*(W_af+W_av))/1000));
fprintf ("DOC_M_AF_L [$/bhr] :                                        ")
disp(DOC_M_AF_L)
fprintf('\n')

DOC_M_AF_M = (30+0.79*(10^-5)*(C_af+C_av));
fprintf ("DOC_M_AF_M [$/bhr] :                                        ")
disp(DOC_M_AF_M)
fprintf('\n')

DOC_M_TJ_L = 1.3 * N_tj*R_l*(0.718+(0.0317*(((W_gto*T_Wgto)*2.2046)/(N_tj*1000))...
    *((1100/TBO)+0.1)));
fprintf ("DOC_M_TJ_L [$/bhr] :                                        ")
disp(DOC_M_TJ_L)
fprintf('\n')

DOC_M_TJ_M = 1.3*((5.43*(10^-5)*C_tj*tj_sppf)-0.47)/(0.021*(TBO/100)+0.769);
fprintf ("DOC_M_TJ_M [$/bhr] :                                        ")
disp(DOC_M_TJ_M)
fprintf('\n')
```

- Total DOC in $/block hours

```
%% TOTAL DOC [$/bhr]

DOC_tot_bhr = DOC_maintenance + DOC_depreciation + DOC_insurance + DOC_crew + DOC_fuel;
fprintf (2,"DOC per Block Hours [$/bhr] :                                ")
disp(DOC_tot_bhr)
fprintf('\n')

fprintf("
```

- DOC in $/flight

```
%% OUTPUT: DOC per flight
fprintf (2,"DIRECT OPERATIVE COST PER FLIGHT ESTIMATE\n")
fprintf('\n')

DOC_fuel_fl= DOC_fuel * (Rt/(680*M*(V_b/V_cr)));
fprintf ("DOC_fuel per flight :                                       ")
disp(DOC_fuel_fl)
fprintf('\n')

DOC_crew_fl= DOC_crew * (Rt/(680*M*(V_b/V_cr)));
fprintf ("DOC_crew per flight :                                       ")
disp(DOC_crew_fl)
fprintf('\n')

DOC_insurance_fl= DOC_insurance * (Rt/(680*M*(V_b/V_cr)));
fprintf ("DOC_insurance per flight :                                  ")
disp(DOC_insurance_fl)
fprintf('\n')
```

- Percentage breakdown of DOC

```
%% OUTPUT: Repartition DOC
fprintf (2,"DOC REPARTITIO\n")
fprintf('\n')

FUEL = DOC_fuel/DOC_tot_bhr *100;
fprintf ("FUEL :                                                      ")
disp(FUEL)
fprintf('\n')

CREW = DOC_crew/DOC_tot_bhr *100;
fprintf ("CREW :                                                      ")
disp(CREW)
fprintf('\n')
```

Within the last section, on the other hand, the lines of code useful for being able to graphic the results presented in the form of $/block hours have been reported.

```
%% Excel data export and Graph

DOC_cost_ripartition = [FUEL, CREW, INSURANCE, DEPRECIATION, MAINTENANCE];
DOC_USD_per_flight= [DOC_fuel_fl, DOC_crew_fl, DOC_insurance_fl, ...
    DOC_depreciation_fl, DOC_maintenance_fl];

%Pie Chart
labels = {'FUEL', 'CREW', 'INSURANCE', 'DEPRECIATION', 'MAINTENANCE'};
pie(DOC_cost_ripartition)
legend (labels)
title(legend, 'DOC Cost Ripartition')
Sheet = 1;
Range = 'B1';
filename = 'DOC_estimation.xls';
```

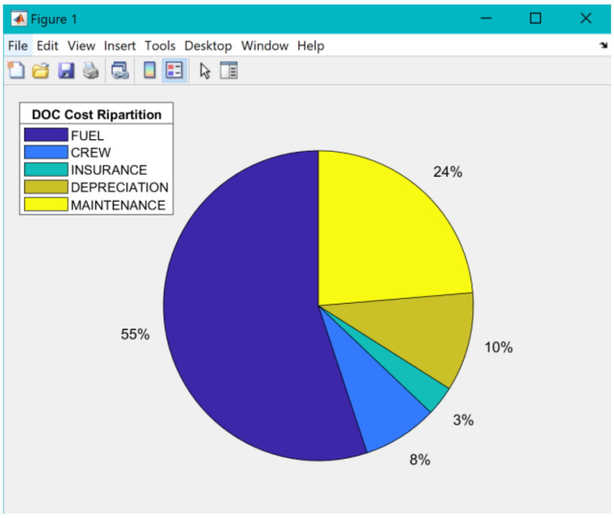
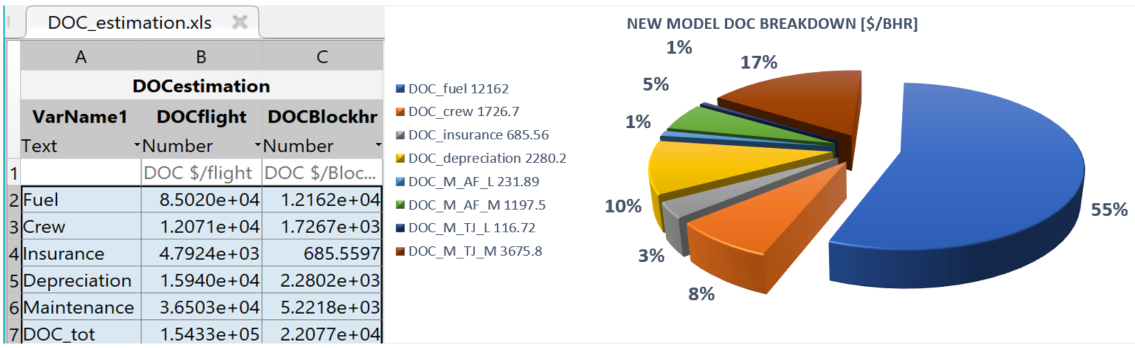


Figure 87 – MATLAB DOC Pie chart

Given the lack of editability of the graphs offered by the MATLAB environment, it was preferred to later introduce new lines of code to be able to export the output values within a spreadsheet (Microsoft Excel).

```
TAB = {'    ', 'DOC $/flight', 'DOC $/Block hr' ; 'Fuel' DOC_fuel_fl DOC_fuel ;...
'Crew' DOC_crew_fl DOC_crew; 'Insurance' DOC_insurance_fl DOC_insurance;'Depreciation'...
DOC_depreciation_fl DOC_depreciation; 'Maintenance' DOC_maintenance_fl DOC_maintenance;...
'DOC_tot' DOC_tot_fl DOC_tot_bhr};
writecell ( TAB , filename , 'Sheet',1,'Range','A1:C7');
```



DOC_estimation.xls

	A	B	C
	DOCestimation		
	VarName1	DOCflight	DOCBlockhr
	Text	Number	Number
1		DOC $/flight	DOC $/Bloc...
2	Fuel	8.5020e+04	1.2162e+04
3	Crew	1.2071e+04	1.7267e+03
4	Insurance	4.7924e+03	685.5597
5	Depreciation	1.5940e+04	2.2802e+03
6	Maintenance	3.6503e+04	5.2218e+03
7	DOC_tot	1.5433e+05	2.2077e+04

Figure 88 – Excel datasheet and Pie chart views

At this point I take the relevant command to start the script will be shown within the command windows all the input values entered and the output values obtained. All these values will be shown within the relevant sections (three input sections and four output sections).

Finally, it is important to underline how the same setting in the script was given to a second script containing within it the CERs related to the cost estimation model proposed by NASA [2].

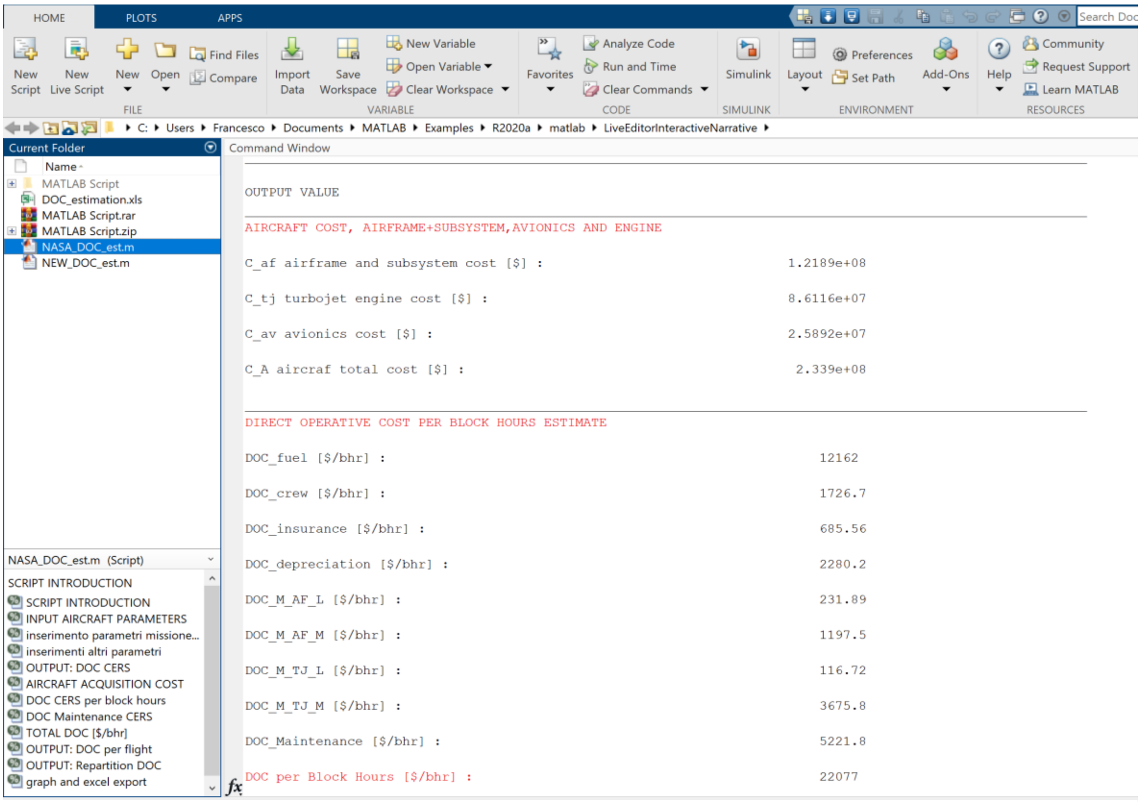


Figure 89 – Output data MATLAB (Command Window)

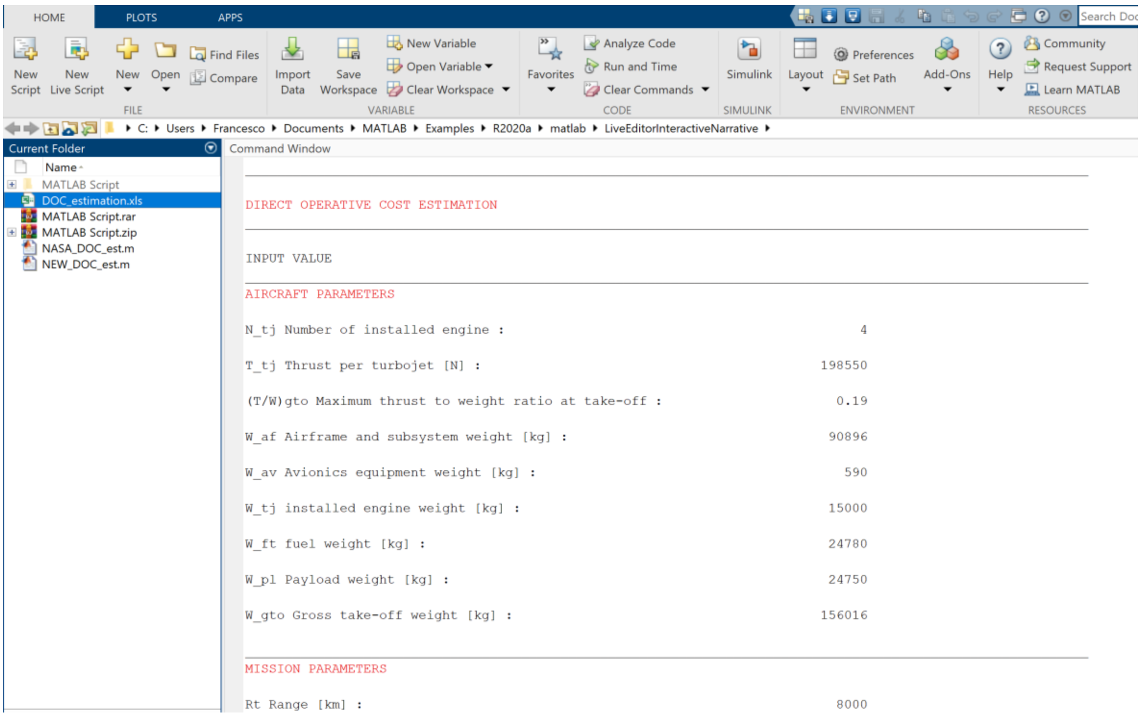


Figure 90 – Input data MATLAB (Command Window)

8. Conclusion

The present thesis work has therefore served to provide a first idea of what may be the operating costs faced by a supersonic aircraft powered by liquid hydrogen. We therefore started from an introduction of the Life Cycle Cost thus going to highlight some key points of the subject of study such as the possibility of using different cost estimation models and as shown by Professor Roskam [3] the enormous difference between the operational costs and the costs incurred in the other phases of life of an aerospace product. We then proceeded, illustrating some key points of the reference aircraft used during the study and of the mathematical cost estimation model (NASA modified ATA 1973 [2]) containing the relative CERs used as a reference basis for the realization of the new cost estimation model. Through the case study and the scripts appropriately developed in the MATLAB environment, it was possible to observe how the percentages of costs are divided within the DOC. The comparison of the entries was an operation of enormous importance since it was necessary during the activity to correct what were the input coefficients going from time to time to refine them with reference values more appropriate than those suggested almost 50 years ago within the NASA model [2]. The real difficult is develop new CERs without a consistent comparison. The data available by the reference for the hypersonic and subsonic aircraft cannot be always used and for this and in some case the data used in the formulation are not precise.

Regarding the values obtained from the case study analysis:

- It was possible to observe once again that fuel-related operating costs are the largest item within direct operating costs. However, as has been observed through the comparison with the other aircraft of the other categories and with the case of price variation in the cost of fuel, there is a value of fuel price per kg such that the item of fuel operating costs is no longer majority within the DOC. It should be emphasized that in this case through the new estimation model used, the cost of the fuel is simply linked to the cost per kg that the latter has on the market and not to its type. More refined models could also take into account the type of fuel adopted as well as the propulsion strategy (the NASA model [2], for example, has a part related to the use of the Breguet formula to evaluate costs based on the range). In this case, the development of these new CERs that take into account new technologies (such as those related to the use of liquid hydrogen here simply assumed as a drop-in technology) will have to be taken into account many experimental data which however are not available at the time of writing this thesis work.

- It is important to observe that for this kind of aircraft the cost of maintenance is extremely high. Supersonic aircraft are by their nature subject to much higher aerodynamic, mechanical and thermal loads than subsonic aircraft and this means their reduced use since they will have to be subjected to many more hours of maintenance which will force them much longer to land with very onerous implications both in terms of maintenance cost and also in terms of depreciation cost.

Referring to the only SST really existed in fact the hours of maintenance per hour flown could reach the ratios 20: 1, this real value is very different from that expected within the NASA model [2] where the ratio hours of maintenance hours flight hours was less than 2: 1, a value suitable only in the case of subsonic aircraft. This large number of extra hours of maintenance leads to an increase in operating costs not considered within the NASA model [2] and therefore to the generation of incorrect values when compared with what can be the values actually supported by a supersonic aircraft.

- From what was shown in the previous point it is possible to observe another fundamental aspect not foreseen at first by this analysis, namely the increase in the cost of depreciation of the vehicle. As is well known for an airline, in order for an aircraft to generate profit, it must be kept operational and therefore in flight as many hours as possible. An aircraft held in place for several miles due to a costly maintenance activity will therefore suffer a strong impact in terms of depreciation cost per mile, which will tend to a much higher value making the vehicle in some cases more competitive or on the market. A similar discourse but with a decidedly lesser impact can also be addressed with regard to the cost related to insurance, even if this kind of cost is again strongly linked to external factors more strictly linked to particular policies that are stipulated between insurance companies and scheduled carriers.

- The Direct operating cost and total operating costs obtained within the case study, however, although they may be in line with the reference costs currently on the market suffer from a certain residual inaccuracy given by the model that however updated it is, suffers once again from the lack of useful reference data for its development. A clarifying example in this sense could be provided by the simple comparison of the ticket price historically offered by the Concorde ($12000) and what was obtained at the end of the case study. Here you can observe how these differ almost by an order of magnitude.

All these important aspects therefore lead to a particular reminder to pay close attention to what are the input values to be included within a mathematical model of cost estimation. Especially given the importance of the role that a correct estimate of costs goes to play. A correct estimate value could therefore lead to the success or commercial failure of an aeronautical project.

All the more so if we take into account the great future changes we are going against. To the great challenges that await us (climate change, possible further pandemics) and that we must necessarily overcome in order to make this kind of business more sustainable in the planet in which we live and that we try to protect.

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