Life cycle cost estimation for high-speed transportation systems

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Life Cycle Cost Estimation for High-Speed Transportation Systems

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This paper presents an innovative methodology and tool developed by Politecnico di Torino and the European Space Agency (ESA) to support Life Cycle Cost (LCC) estimation for High-Speed Transportation Systems. This ad-hoc built-in tool aims at supporting engineers in cost estimations during conceptual and preliminary design phases. This includes the evaluation of Research, Development, Test and Evaluation Costs (RDTE costs), Production costs as well as Direct and Indirect Operating Costs (DOC and IOC). Eventually, results of the LCC evaluation for two different High-Speed Transport vehicles are provided and discussed.

Keywords: Life-Cycle Costs Estimation, Cost Estimation Relationships, Hypersonic Transportation System, Impact of Technologies on Cost Estimations.

Nomenclature

AEA – Association of European Airlines
APU – Auxiliary Power Unit
ATA – Air Transport Association of America
ATR – Air Turbo Rocket
AVIO – Avionic System
CAV – Cruise and Acceleration Vehicle
CER – Cost Estimation Relationship
CpF – Cost per Flight
ICAO – International Civil Aviation Organization
INT - Integration
IOC – Indirect Operating Costs
LAPCAT – Long-term Advanced Propulsion Concepts And Technologies
LCC – Life Cycle Cost
LDG – Landing Gear
LH_2 – Liquid Hydrogen
LR – Launch Rate

DMR – Dual Mode Ramjet

DOC – Direct Operating Cost

DOC+I – Direct Operating Costs + Interest

Dr – Driver Parameter

ECS – Environmental Control System

ELV – Expendable Launch Vehicle

EPS – Electrical Power System

EU – European Union

FAA – Federal Aviation Administration

FCS – Flight Control System

FPS – Fire Protection System

FUEL – Fuel System

FY – Fiscal Year

GUI – Graphical User Interface

HYD – Hydraulic System

HST – Hypersonic Transport

IATA – International Air Transport Association

IPS – Ice Protection System

NASA – National Aeronautics and Space Administration

OEW – Operating Empty Weight

PBS – Product Breakdown Structure

RDTE –Research, Development, Test and Evaluation

REL – Reaction Engines Limited

RJ - Ramjet

RLV – Reusable Launch Vehicle

SI – International System of Units

STRUCT - Structure

TFU – Theoretical First Unit

TJ – Turbojet

TOC – Total Operating Cost

TP – Technology Parameter

TPS – Thermal Protection System

US – United States

VEMS – Vehicle Energy Management System

WBS – Work Breakdown Structure

WYr – Work-Year

1. Introduction

The assessment of the economic feasibility of the vehicle and its mission concept is currently considered one of the major challenges of the design of high-speed vehicles. As mentioned by Roskam [1], the costs sustained by an airline to operate an aircraft through the years constitutes the greatest part of the costs incurred during the overall product life cycle. Nowadays, in the aeronautical domain, Life Cycle Cost (LCC) can be estimated since the very beginning of the design process thanks to the availability of databases and statistical data. It is mainly for this reason that many of the currently available predictive models cannot be applied to the costs estimations for vehicles characterized by a very high level of innovation. This is the case of hypersonic vehicles. The activities carried out by Politecnico di Torino aspire to overcome these issues developing parametric models able to predict the LCC of a high-speed transportation system. In particular, in this context, the focus is on a hypersonic aircraft able to perform point-to-point transportation usually referred to in literature as Cruise and Acceleration Vehicle (CAV) [2]. In addition, advanced algorithms have been developed to predict the impact of necessary technological improvements on operating costs.

After this short introduction, summarizing the main reasons for this research activity as well as its main objectives, Section 2 briefly summarizes the results of the literature review performed to understand the approaches currently used in the aviation and in the aerospace domains. Section 3 begins with a schematic description of the methodology developed by Politecnico di Torino, taking advantage of some existing cost estimation procedures, and then provides details on the developed algorithms. Section 4 focuses on HyCost, the tool developed at Politecnico di Torino to implement the methodology as described in the previous section. Ultimately, Section 5 provides a description of the application of the developed methodology to different case studies. In particular, two of the reference configurations developed in the framework of LAPCAT I [3] and LAPCAT II [4] projects are considered: the LAPCAT A2 and LAPCAT MR2.4, clear examples of two point-to-point hypersonic passenger/cargo aircraft. At the end of the present article, main conclusions are drawn and ideas for future developments of the tool are reported.

2. Existing operating costs estimation models

An in-depth literature review was carried out and the results confirmed only the existence of cost estimation models that could be partially applied to the present study. In particular, TransCost model [5] was taken into account, especially as a base for the derivation of the Research, Development, Test and Evaluation (RDTE) as well as production Cost Estimation Relationships (CERs). As far as Direct Operating Cost (DOC) is considered, different approaches proposed by Air Transport Association of America (ATA) [6], Association of European Airlines (AEA) [7], and Liebeck [8] were extended to hypersonic applications despite of being specifically tailored to their reference vehicle architecture. National Aeronautics and Space Administration (NASA) suggested a more generic approach in 1973. In particular, [9] was adopted as reference model, because it allows evaluating the impact of breakthrough technologies onto DOC. The proposed equations for DOC estimation are a modified version of the ATA [6].

Operating cost estimation is usually split into Direct Operating Cost (DOC) and Indirect Operating Cost (IOC). The former family concerns flight operations, including the costs related to fuel, oil, crew, maintenance, depreciation and insurance. Depreciation cost takes into account the "allocation of the purchase price out over a number of years, using some depreciation schedule" [10]. Furthermore, landing fees, carbon and noise taxes and other government charges (like navigation charges) shall be included into DOC. Interest cost, which derives from the need of airlines to borrow money with a certain rate of interest in order to finance the entire project, could be considered as part of DOC as well. Complementary, IOC category encompasses all the rest of operating expenses, like the depreciation cost of ground facilities and equipment, the sales and customer service costs, and the administrative and overhead costs.

The present work specifically deals with the cost items gathered and defined in **Errore. L'origine riferimento non è stata trovata.**. Moreover, **Errore. L'origine riferimento non è stata trovata.** is an example of DOC breakdown for a hypersonic point-to-point vehicle directly taken from NASA [11]. It can be noticed that the largest part of DOC for a hypersonic cruiser (if fueled with Liquid Hydrogen (LH_2)) is represented by the fuel cost. This is mainly due to the type of propellant exploited, and, in case LH_2 is selected, to the currently available LH_2 production scenarios (that would certainly drop if mass production will be in place). **Errore. L'origine riferimento non è stata trovata.** also allows comparing the percentage DOC splitting for a hypersonic cruiser with the typical values obtained for a wide-body subsonic kerosene-fueled aircraft with more than 300 seats [12]. It can be noticed that, in both cases, the fuel cost constitutes the most demanding cost item. It is underlined that, the absolute values of DOC obtained for the two different vehicle categories are quite different. In particular, as reported also by Federal Aviation Administration (FAA) [12], the typical overall DOC value (scaled to Fiscal Year (FY) 2017) for a wide-body aircraft is around €15,000 per block hour. The block hour can be defined as the unit of measure of the mission time, encompassing the time spent by the aircraft from initial movement prior to taxi and take-off up to final engines shut down, including both the time spent on ground and in-flight. For hypersonic vehicles, according to estimations performed in the past by Reaction Engines Limited (REL), the DOC amounts to almost €285,000 per block hour. The great difference in the absolute value of DOC/block hour reflects the difference fuel types (Jet-A vs LH_2) and related prices (i.e. 4.25 €/kg vs 0.49 €/kg). It is clear that the difference in the cost per block hour between hypersonic cruiser and wide-body aircraft could be reduced by decreasing the gap between the two fuel price values. This could be performed, for example by improving the LH_2 production process, increasing the production rate and developing new technologies to reach a more cost-effective transport of cryogenic fuel to the airport premises.

Moreover, the difference in DOC/block hour allows explaining the lower percentage value (**Errore. L'origine riferimento non è stata trovata.**) for the DOC of crew of a hypersonic vehicle if compared to the corresponding value for a wide-body aircraft. In account of this, it is worth noticing that the flight crew cost usually slightly varies between the different aircraft categories. Therefore, it could be plausible that for both hypersonic vehicles and wide-body aircraft the DOC crew item would have a similar value as well.

For sake of clarity, please, notice that all along the paper, an exchange rate from € to $ of 1.13 is used to convert all the costs to FY2017. In addition, all the costs coming from different sources have been converted to FY2017 to allow comparisons, using proper exchange rates.

Table 1. DOC splitting for a hypersonic point-to-point vehicle from [11] and for a wide body aircraft from FAA [12]

Cost Item	**Definition**	**DOC %**	
		Hypersonic Cruiser	**Wide body Aircraft (more than 300 seats)**
Crew	Flight crew cost, including captain, co-pilots and flight engineers	0.98	10.78
Fuel	Fuel cost	68.63	72.00
Insurance	Ground and flight risk of experiencing airframe damage or total loss Passenger liability in case of injury or death Third party liability in case of injury or death Cargo damage risk	2.45	0.06
Maintenance	The labor and material cost of maintaining airframe and engines.	18.14	11.82
Depreciation	Depreciation cost refers to the "allocation of the purchase price out over a number of years, using some depreciation schedule". [1]	9.80	5.33

In the aeronautical field, several methodologies based on airline statistical data exist and can be exploited in order to estimate both DOC and IOC. Being based on statistical population, some of the correlations suggested by these approaches are outdated and might be enhanced with more recent aircraft data in order to reflect actual costs. Moreover, pure statistical approaches can lead to inappropriate estimations considering the quite absolute lack of real data coming from hypersonic vehicles operations. Nevertheless, they constitute a useful base for the development of tools for preliminary operating cost assessment. Among the state-of-the-art methods for DOC, the ATA method [6] is very interesting because it provides a set of empirical equations able to calculate the following cost items: flight crew cost, fuel cost, maintenance cost, depreciation and insurance cost. This method represents the first standardized approach for the evaluation of the operating cost of subsonic jets. Another noteworthy approach is the Direct Operating Cost plus Interest (DOC+I) method proposed by Liebeck et al. [8] for DOC assessment. The DOC+I method represents an update of the ATA method [6] and provides CERs to estimate flight and cabin crew costs, maintenance cost, landing fees, navigation fees, fuel cost, depreciation, interest and insurance cost. Other methods for aircraft DOC estimation are, for example, the AEA method [7], published in 1989, and the Roskam method [1], which provides CERs for the evaluation of the entire LCC for both civil and military aircraft.

Conversely, in the space field, the TransCost model [5] constitutes a fundamental reference for cost assessment, especially for space launchers. It is a statistical and analytical model applicable during the initial conceptual design phase of space transportation systems and engines. It provides CERs for development, production, ground and flight operations costs at system level based on actual space vehicles and engine projects data. Moreover, it was conceived to provide cost estimations for reusable space transportation systems too. The main cost drivers of TransCost CERs for ground and flight operations costs (i.e. the analogous of the afore-mentioned DOC and IOC) are the vehicle launch mass, the number of stages, and the launch rate. The TransCost Model does not provide specific CERs for the DOC assessment of hypersonic cruisers. As already mentioned, it is a space-oriented approach, taking into account cost elements specifically referred to space vehicles operations, e.g. launch preparation and path refurbishment, transportation to the launch site, tracking and data relay operations. These items are summarized in **Errore. L'origine riferimento non è stata trovata.**.

In addition, the cost estimating models summarized by Wertz in [13] can be considered as useful reference, especially for some DOC items that are not strictly related to the mission itself.

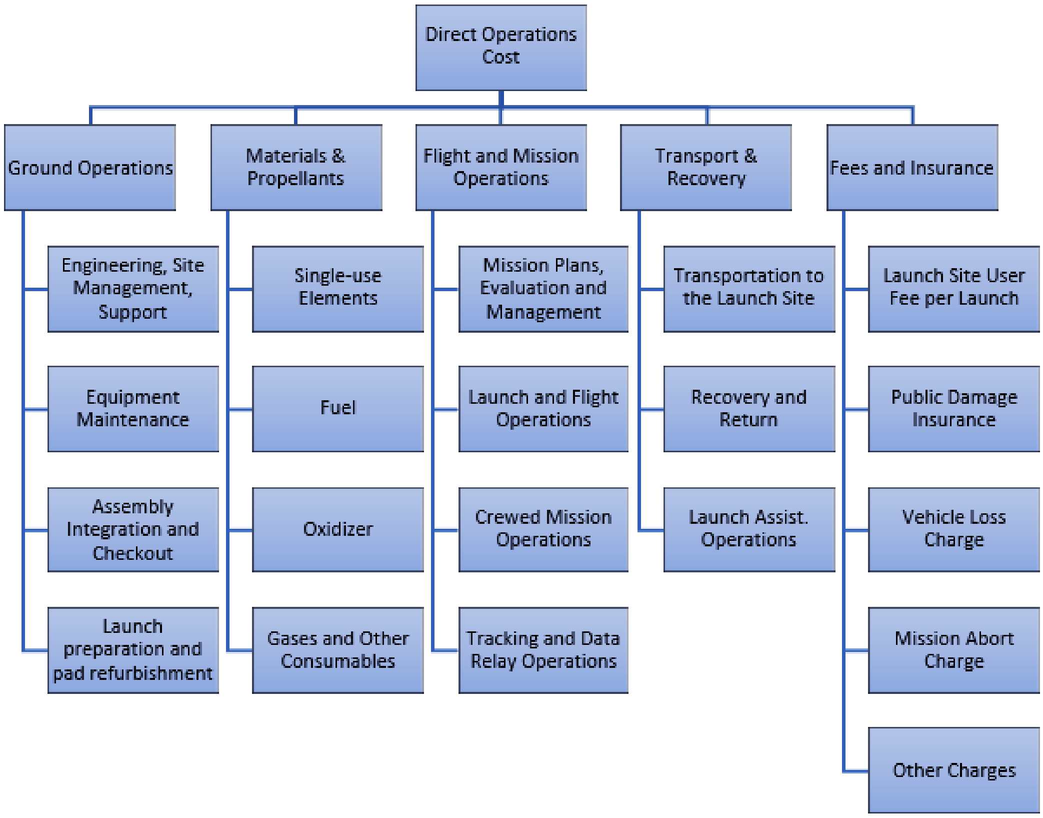

Fig 1. DOC item breakdown (following TransCost Model [5])

In order to properly evaluate the DOC of a hypersonic vehicle intended to be operated similarly to a civil aircraft both in terms of mission and functionalities, an aeronautical-oriented cost estimating approach is required. The approach should be able to provide a set of CERs following a formalism similar to those proposed by the ATA [6], AEA [7] or Liebeck [8] methodologies but specifically adapted to the hypersonic case. NASA has already proposed a similar approach in 1973 [9]. In particular, this NASA work [9] provides a complex methodology which, starting from the DOC cost assessment, allows to evaluate the impact of breakthrough technologies onto DOC. The proposed equations for DOC estimation are already a modified version of the ATA CERs [6] taking into account, through proper coefficients, the greater maintenance effort in terms of labour and materials required for hypersonic cruisers. These equations constitute a first attempt to quantify the costs to operate hypersonic vehicles. Indeed, since the 1970s, it was clear that the major issue to overcome was the fact that these vehicles have not yet been produced and no real statistical cost data (which could constitute a database for new CERs derivation) were available in literature. Therefore, starting from the available aeronautical data, only predictive cost evaluations that would consider the foreseen increased complexity related to these new concepts can be performed. In this sense, the NASA method [9] is a fundamental tool as it provides some important considerations to deal with the greater complexity of hypersonic cruisers starting from some available statistical data on supersonic vehicles. In this context, the research activities carried out by Politecnico di Torino focused on the analysis of the set of equations provided by NASA [9], evaluating the applicability to the reference case study, on the identification of changes to be implemented in order to update these CERs and on the development of an activity flow in which the modified CERs can allow to predict the impact of technological improvements onto DOC.

As far as IOC is concerned, only few existing methodologies provide CERs to estimate this operating cost contribution. This is mainly because indirect costs are often determined at airline level and not at aircraft level and, thus, they are estimated in conceptual design only as a percentage of DOC. Indeed, they are strictly related to specific airline operating strategies and may consistently vary from one airline to another. In particular, the Roskam method [1] provides some useful guidelines for IOC assessment.

3. Innovative cost estimation methodology overview

3.1. Methodology Overview

Fig. 2 summarizes the major steps of the developed methodology and the existing models that were taken as reference for the different elements constituting the methodology. In particular, the most innovative contents are in the 1st, 3rd and 4th steps of the methodology here proposed, i.e. on the development of estimation models to predict the impact of technological improvements as well as the effect of different flight rates on DOC. However, this article is only qualitatively describing the methodology laying behind the 3rd step (Section 3.4), since the research activity performed by Politecnico di Torino is not yet completed in this field and more details can be found within the work published by NASA in the '70s [9]. The overall approach is based on the modification of DOC equations to include additional parameters, or group of them, making the final DOC equation able to predict the effects of technological improvements.

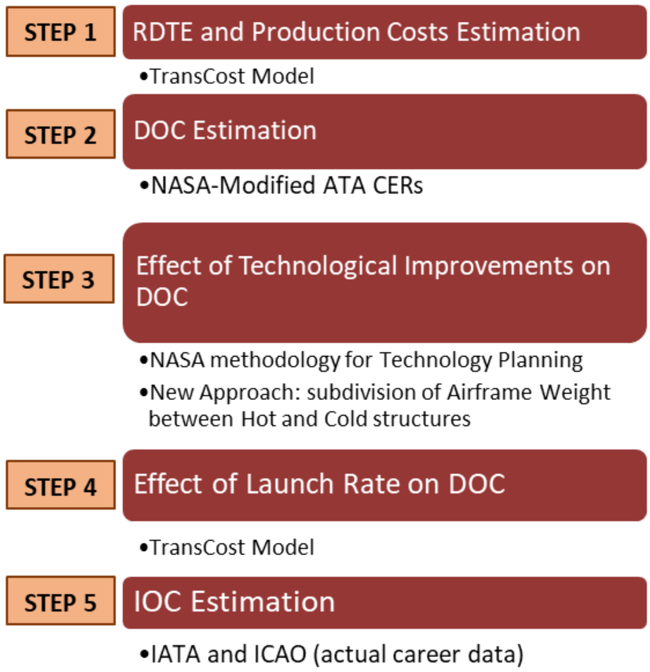

Fig 2. Methodology overview

3.2. RDTE and Production Cost Estimation Relationships

RDTE as well as production CERs for a high-speed vehicle have been derived based on semi-empirical models in which the equations are expressed as follows:

$$C_{item} = \sum_{i=1}^{N_{drivers}} A_i D_i^{\alpha_i} \qquad (1)$$

where

- C_{item} is the cost associated to a certain item;
- i is the index accounting for each driver;
- A_i is the cost impact factor of the ith driver;
- α_i is the exponent of the ith driver D_i;
- D_i is the value for ith driver.

This equation can be considered as an expansion of the formulation proposed in TransCost [5]. Indeed, with the exploitation of a small database of past initiatives on supersonic and hypersonic vehicles and a reference cost model developed in Price TruePlanning [14], CERs are proposed for all the subsystems of interest in contrast to TransCost, in which formulations are provided only at airframe and engines level. In addition, the CERs developed by Politecnico di

Torino allow to understand the dependency of the cost item from a great variety of cost drivers, facilitating the evaluation of the impact of technological improvements on them. Fig. 3 reports a typical CER derived for production costs and its graphical interpretation. Further details concerning the new CERs can be found in [14], whilst the complete list of equations is reported in Appendix I. Please, note that in Fig.3:

- F'_{VF} is the production cost for high speed advanced aircraft in M€ (FY2017) ;
- $M_{T_{OEW}}$ is the Operating Empty Weight of the aircraft in tons;
- $\boldsymbol{v_k}$ is the aircraft cruise speed in km/h;
- f'_{10} is the cost reduction factor, taking into account a reduction in production cost due to technical progress and application of cost engineering. It ranges between 0.7-0.85 [5].

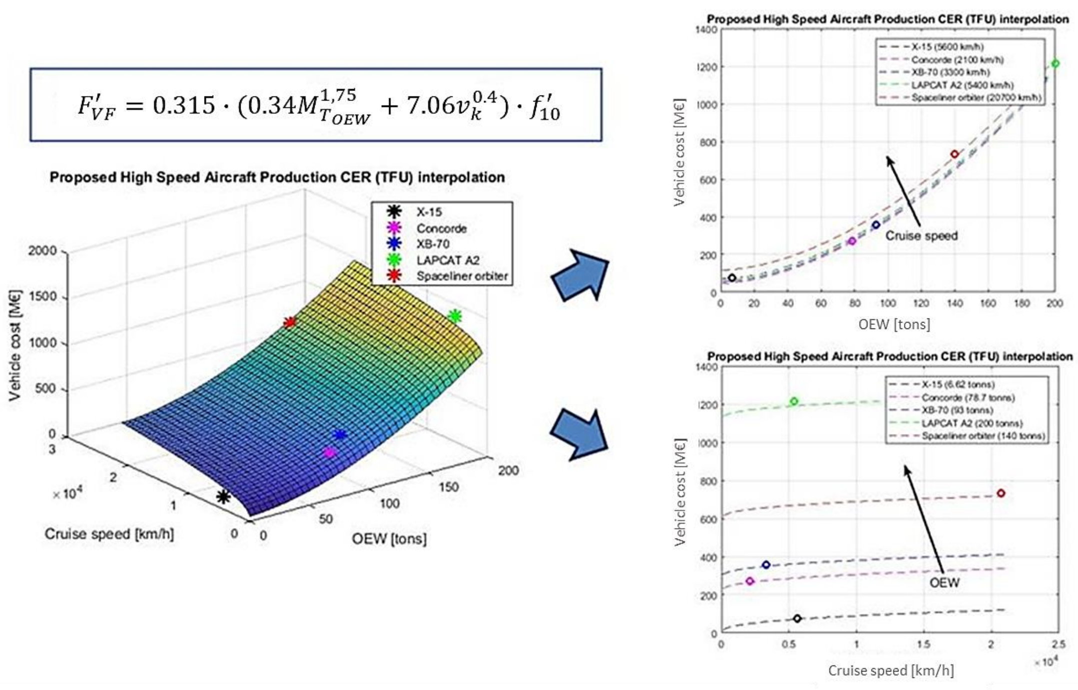

Fig 3. CER for Overall Aircraft Production

Please, notice that the CERs reported in Appendix make use of Work-Year (WYr) [5] instead of local currencies. This is a well-established approach that facilitates comparisons without requesting currencies conversions.

3.3. DOC Estimation Relationships

NASA modified ATA model [9] has been considered as reference model for the generation of a basic set of equations allowing the estimation of DOC for a baseline configuration. In particular, a set of five major equations have been analyzed and considered applicable: insurance, depreciation, flight crew, fuel and maintenance. Moreover, considering the complexity of the maintenance CER, equations for six different components have been included: airframe labor, airframe material, turbojet labor, turbojet material, (sc)ramjet labor and (sc)ramjet material. Additional details on these equations are provided in Appendix II.

3.4. Impact of technological improvements on DOC

The basic set of equations introduced in the previous section does not contain explicit reference to the exploitation of specific technologies. For this reason, the following mathematical relationship is introduced:

$$DOC_{item} = f_1\{cost\ driver_j[f_2(technological\ parameter_i)]\} \quad (2)$$

According to this equation, the generic DOC item can be expressed as a function of j-th cost driver. The j-th cost driver can, in turn, be expressed as a function of i-th technological parameter. In account of this, the logic flow of the whole methodology [9] can be resumed by the following equation:

$$\Delta DOC_{ij} = (DOC)_{BL} \cdot \left(\frac{\Delta DOC/DOC}{\Delta Dr/Dr}\right)_j \cdot \left(\frac{\Delta Dr/Dr}{\Delta TP/TP}\right)_{ij} \cdot (\Delta TP/TP)_i \quad (3)$$

Where:

- ΔDOC_{ij} is the delta-cost on a generic DOC item due to the i-th technological improvement on the j-th cost driver;
- DOC_{BL} is the value of the generic cost item calculated for the baseline configuration;
- $\left(\frac{\Delta DOC/DOC}{\Delta Dr/Dr}\right)_j$ is called "Driver Partial" and relates the change in the generic DOC item to the j-th Driver Parameter (*Dr*), i.e. the cost driver;
- $\left(\frac{\Delta Dr/Dr}{\Delta TP/TP}\right)_{ij}$ is called "Technology Parameter Partial" and relates the change in the j-th Driver Parameter to the i-th Technology Parameter (*TP*);

- $(\Delta TP/TP)_i$ is the foreseeable i-th technological improvement in the baseline Technology Parameters.

Fig. 4 summarises the algorithm suggested to solve this equation, reporting a specific example dealing with the attempt of tracing the impact on maintenance cost of the introduction of integral tankage in the fuselage, aiming at reducing the overall vehicle mass.

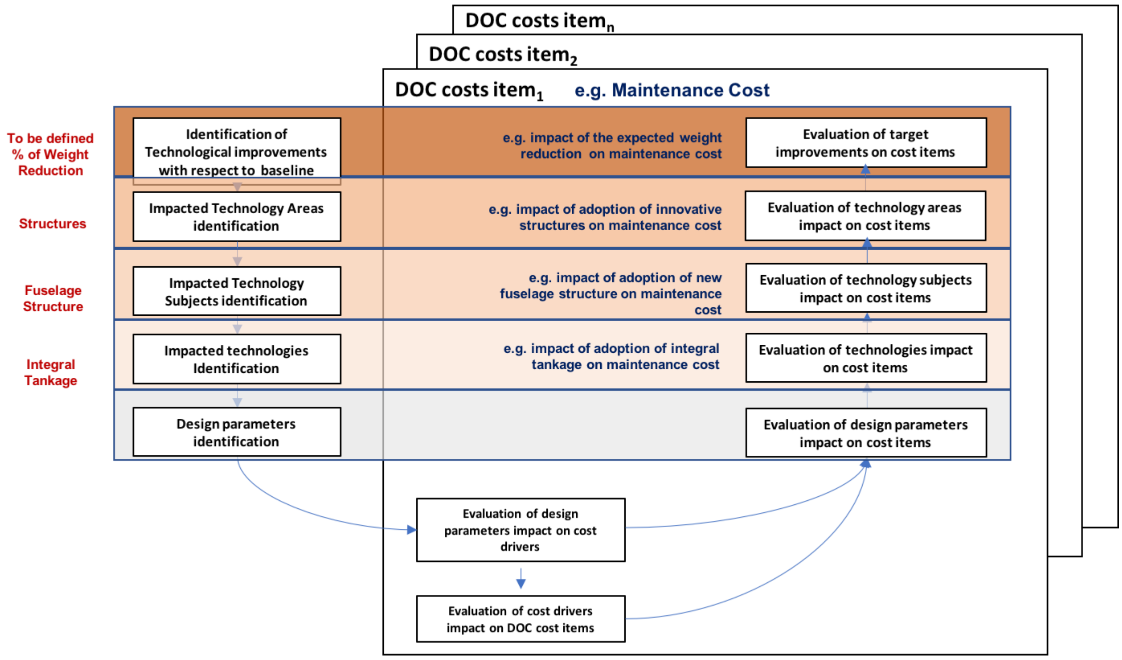

Fig 4. Algorithm for the evaluation of the impact of technological improvements on DOC

3.5. Effect of Flights per Year on DOC

The aim of this section is to suggest a suitable way to evaluate the effect of a variation in the launch (or flight) rate (LR), i.e. the number of flights per year on DOC. The basic idea is to start from the "Power Law" provided in TransCost [5], which expresses the trend of Cost per Flight (CpF) as a function of the LR and to derive a new set of parametric equations to be used for under-development hypersonic transportation systems. In order to tune the parametric model, the available results for the LAPCAT A2 vehicle cost estimation performed by REL have been used [15]. In particular, the final goal is to build a curve of DOC as function of LR, i.e. a DOC curve, valid for LAPCAT A2 vehicle. The general validity of the cost breakdown has been confirmed by the comparison with the NASA DOC breakdown for hypersonic vehicles [11]. In order to allow the comparison, the NASA model [11] was updated with a more realistic fuel cost per kg. The results of this activity are reported in Fig. 5, together with the estimation relationships for the LAPCAT A2 vehicle as well as for the NASA approach [11] (see Eq. (4) and Eq. (5) respectively).

$$(DOC)_{LAPCAT} = 9.2327 \cdot LR^{-0.341} \tag{4}$$

$$(DOC)_{NASA} = 5.3769 \cdot LR^{-0.341} \tag{5}$$

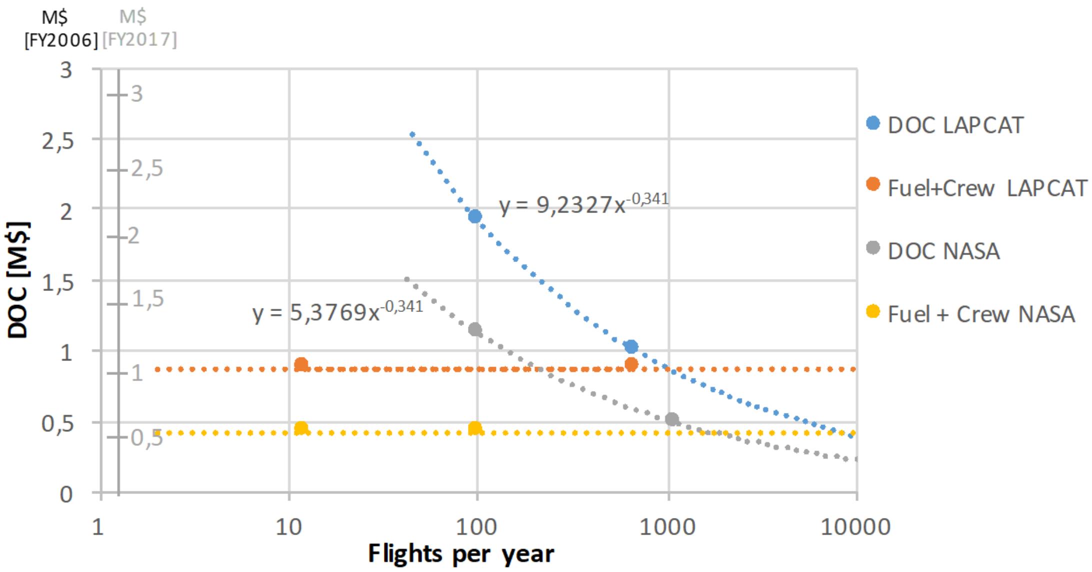

Fig 5. Effect of LR on DOC

Looking at Fig.5, it is important to underline that the DOC curve for LAPCAT A2 (and the "Fuel+Crew cost" curve) are obtained using the fuel cost suggested by REL, i.e. 4.25 €/kg (2.18 $/lb) for FY2017 (or 3.5 €/kg (1.99 $/lb) for FY2006). Please, note that Fig.5 reports costs both for FY2006 and for FY2017: this is due to the fact that original REL data for fuel cost were reported for FY2006). Conversely, the DOC curve for the NASA Vehicle [11] (and the "Fuel+Crew cost" curve) are obtained using the fuel cost for FY2017 of 2.7 €/kg (1.54 $/lb) (or 2.22 €/kg (1.27 $/lb) for FY2006). This value is the result of a recent in-depth investigation on LH_2 cost performed by Politecnico di Torino and reported in [16].

3.6. Ground Infrastructure Cost Evaluation

As depicted in Fig.1, Ground Operations Cost should be included into DOC assessment. In particular, in order to properly assess the amount of resources needed to fully operate a hypersonic cruiser, it is necessary to evaluate the cost associated to ground facilities and, in particular, to the development of spaceports able to handle the operations of future high-speed transportation systems. However, considering the novelty of the application and the scarce available statistical population, the evaluation of the impact of ground infrastructures onto DOC is a challenging activity. In addition, TransCost Model [5] does not provide specific guidelines to assess this cost contribution. To solve the problem, a preliminary assessment of spaceport costs based on an extensive literature review has been carried out.

More specifically, Gulliver et al. [17] state that the envisaged development cost for a spaceport able to support future Reusable Launch Vehicles (RLVs) operations ranges between 91.5 M€ (103.39 M$) to 457.5 M€ (516.41 M$) in FY2017 (or 100 M$ to 500 M$ in FY2014 as reported in [17]). Additional costs to certify and licence the site according to FAA requirements shall be considered as well. This contribution can be estimated at around 0.91 M€ (1.03 M$) in FY2017 as stated in [17]. This theoretical trend, seems to be in line with some actual data. Indeed, for example, the development cost for Spaceport America [18] seems to perfectly fit into the range 91.5 M€ to 457.5 M€, considering the value reported in [17] i.e. 183 M€ in FY2017(or 200 M$ in FY2014 as in [17]).

It is worth noticing that the data introduced above are associated to space transportation systems (i.e. RLVs) which will perform different missions (orbital or suborbital) with respect to the hypersonic point to point cruisers treated in the present article. Nevertheless, the proposed values constitute a good benchmark for a preliminary economical assessment, providing a conservative estimation of expected ground infrastructure costs.

To provide a more precise cost assessment, the factors impacting on ground infrastructure characteristics should be carefully considered. Among them, it is worth to keep into account [17],[19]:

- The vehicle concepts for which the spaceport is designed (e.g. RLVs might require an extended runway length);
- The types of missions operating from the spaceport;
- The propellant types used on vehicles, which strongly influence required gas facilities and safety procedures;

- The spaceport location, which impacts on its roles and capabilities (e.g. the possibility to perform suborbital flights for space tourism) [20];
- The type of take-off and landing capabilities supported by the spaceport or, more in general, the vehicle orientation;
- The flight rate, impacting on facility and equipment utilization, which allows to split the non-recurring ground infrastructures cost on a higher number of flights per year, speeding up spaceport costs amortization.

In particular, the flight rate is a very interesting parameter to be exploited for a more precise assessment of costs for ground facilities development. In particular, as suggested by Penn [21], the annual infrastructure cost can be estimated as a function of flight rate (Table 2), including the derived infrastructure cost per flight. From Table 2 it can be noticed that, increasing the flight rate, the infrastructure cost per flight decreases because the total non-recurring cost for support infrastructures is split among a greater number of flights. The data on infrastructure cost and flight per year gathered in Table 2 have been graphically depicted in Fig.6 in order to explicitly derive the mathematical relationship among ground infrastructure cost and flight rate. Please, note that original cost data reported in [21] were referred to FY2003. The latter have been properly converted to FY2017 and reported, both in € and in $, in Table 2.

Table 2. Ground Infrastructure Cost as a function of Flight Rate derived from [21]

Infrastructure cost, M€/year (M$/year), FY2017	**Flights/year**	**Infrastructure cost per flight M€/year (M$/year), FY2017**
353 (399)	10	35.31 (39.9)
353 (399)	50	7.06 (7.98)
412 (466)	100	4.12 (4.66)
471 (532)	1000	0.47 (0.53)
471 (532)	5000	0.09 (0.11)
706 (798)	10,000	0.07 (0.08)

For example, recalling the cost data suggested in [17] for new spaceport development and considering the values shown in Table 2, it might be possible to estimate which should be the minimum number of flight per year from a single spaceport, to have a sustainable depreciation plan for the newly developed on-ground infrastructure. In particular, assuming as spaceport development cost the "worst" case reported in [17] (i.e. 500 M$ in FY2014 or 457.5 M€ in FY2017) and exploiting the regression equation shown in Fig.6, a total amount of 2,561 flights, are required to fully amortize spaceport cost in a year of operations. In case, for example, the high-speed flights are performed by LAPCAT vehicles, each of them able to carry out 550 flights per year as specified in [22], a fleet of 5 vehicles might be sufficient to cover the expenses for the infrastructure costs during the first year of operations.

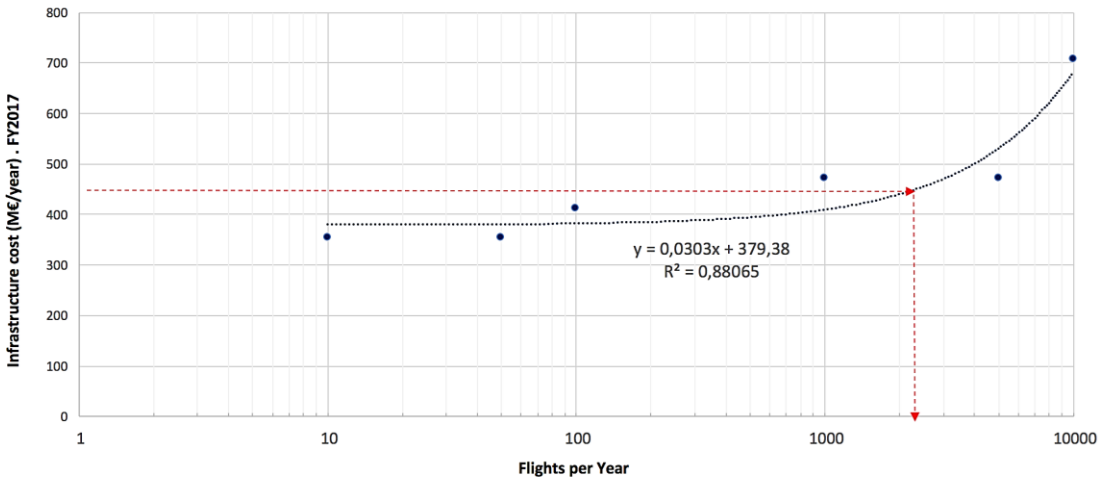

Fig 6. Infrastructure Cost per Flight as a function of Flight Rate

3.7. IOC Estimation Relationships

Generally, it is quite difficult to find in literature an affordable method for IOC assessment for civil aircraft, able to reflect actual indirect costs incurred during aircraft operations. It is principally due to the consistent lack of IOC data and to the fact that indirect cost is strictly related to the specific airline, considerably varying between major airlines, low-cost carriers, regional airlines and so forth. Difficulties increase when hypersonic vehicles are tackled, taking into account that they represent a complex mixture of aircraft and space vehicle characteristics. Concerning space vehicle IOC, the TransCost methodology [5] provides useful guidelines (even though CERs are not directly included) for both Expendable Launch Vehicles (ELVs) and RLVs IOC determination. However, the differences in terms of mission profile between space vehicles and hypersonic transportation and the idea that, in the future, there will be airlines with hypersonic vehicles in their fleet, lead to the consideration that for hypersonic vehicles the IOC data provided by IATA [23] and ICAO [24], currently in use in aeronautics, can be more properly exploited as a reference.

However, considering the future target of the studied hypersonic transportation (i.e. to behave as a traditional civil aviation vehicle), it can be expected that IOC will not change considerably. Moreover, the IATA [23] and ICAO [22] data are quite recent and reliable.

4. HyCost Tool

The overall methodology and related algorithms presented in Section 3, was implemented in an ad-hoc built-in tool developed by Politecnico di Torino in a Matlab environment supported by a Graphical User Interface (GUI), with the aim of supporting engineers with LCC estimation during the conceptual and preliminary design phases. The figures shown in Appendix III are examples of input (Fig.12 and Fig.13) and output windows (Fig. 14) of the tool. Important efforts were placed in the development of an element in the HyCost tool allowing the user to change the design parameters and "live" appreciating the impact on costs estimation (Fig. 15).

First of all, it has to be noticed that the tab-like concept of the tool is extremely useful to work with input data during the typical iterative process characterizing the conceptual and preliminary design phase, especially for highly innovative concepts, such as those for high-speed transportation. The input tab requests the propulsion system characteristics as well as some other values important to characterize the type of vehicle under investigation. In addition, a specific section of this tab is related to the definition of the propellant used by the vehicle as well as of its production scenarios that might represent one of the key aspects. An interesting view of this specific tab is provided in Fig. 13, where the user has also the possibility of creating a customized learning curve (see [1] for more details), making a forecast of the maximum number of units produced for each vehicle.

The output tab was developed to provide the user with an effective communication of the results, by means of pie-charts supported by tables, in which the numerical results can be accessed (Fig.14). Ultimately, the cost variation prediction due to technological improvements was implemented, together with the possibility for the user to modify several parameters, exploiting sliding bars, and to directly see the impact on cost results (Fig. 15).

5. HyCost Applications

The overall LCC methodology was applied to the LAPCAT A2 and LAPCAT MR2 [4],[25]. Considering the RDTE and production costs, a cost breakdown up to subsystem level was defined. Even if the proposed LCC estimation also supports the evaluation of on-board subsystems, the results reported in this section have a higher granularity in order to make the comparison possible with existing estimations performed by REL in 2006, which was solely focusing on the Scimitar Engine [26] and vehicle airframe items. Table 3 reports the results for RDTE cost estimation while Table 4 and Table 5 summarize the production costs for both the Theoretical First Unit (TFU) produced as well as for the 200th unit (i.e. the last one), showing the impact of the learning factor. The results are reported in € for both FY2017 and FY2006 for comparison with the evaluation performed by REL. In order to provide a comparison for last unit cost, the estimations coming from REL are extended for a production run of 200 units.

Table 3. RDTE cost estimation for LAPCAT A2

Cost Item (LACPAT A2)	**REL Model M€ FY2006**	**HyCost Model M€ FY2006**	**HyCost Model M€ FY2017 (M$ FY2017)**
Scimitar	8147	5927	8286 (9363)
Airframe	14,454	11,837	16,550 (18,701)
Vehicle	**22,601**	**17,764**	**24,836 (28,065)**

Table 4. Production cost estimation for LAPCAT A2 TFU

Cost Item (LAPCAT A2)	**REL Model M€ FY2006**	**HyCost Model M€ FY2006**	**HyCost Model M€ FY2017 (M$ FY2017)**
Scimitar (average engine cost for TFU)	67	77	108 (122)
Airframe	712	643	900 (1017)
Vehicle	**979**	**951**	**1332 (1505)**

Table 5. Production cost estimation for LAPCAT A2 200th unit produced

Cost Item (LAPCAT A2)	**REL Model M€ FY2006**	**HyCost Model M€ FY2006**	**HyCost Model M€ FY2017 (M$ FY2017)**
Scimitar (average engine cost for 200th vehicle)	22	26	37 (42)
Airframe	265	122	170 (192)
Vehicle	**353**	**226**	**318 (359)**

The results derived from the model proposed in this study show a lower development cost for both engine and airframe if compared to REL analysis (Table 3). Production costs are instead in line, even if a more effective learning curve is used for the proposed model (cost reduction based on REL analysis is slower considering the same number of units). An overview of the detailed results on Product Breakdown Structure (PBS) and Work Breakdown Structure (WBS) is reported in pie-charts of Fig.7 and Fig.8. The main contributions for both RDTE and production costs are coming from structure and powerplant. Integration development plays a very important role in RDTE breakdown, even if it is less important within production activities.

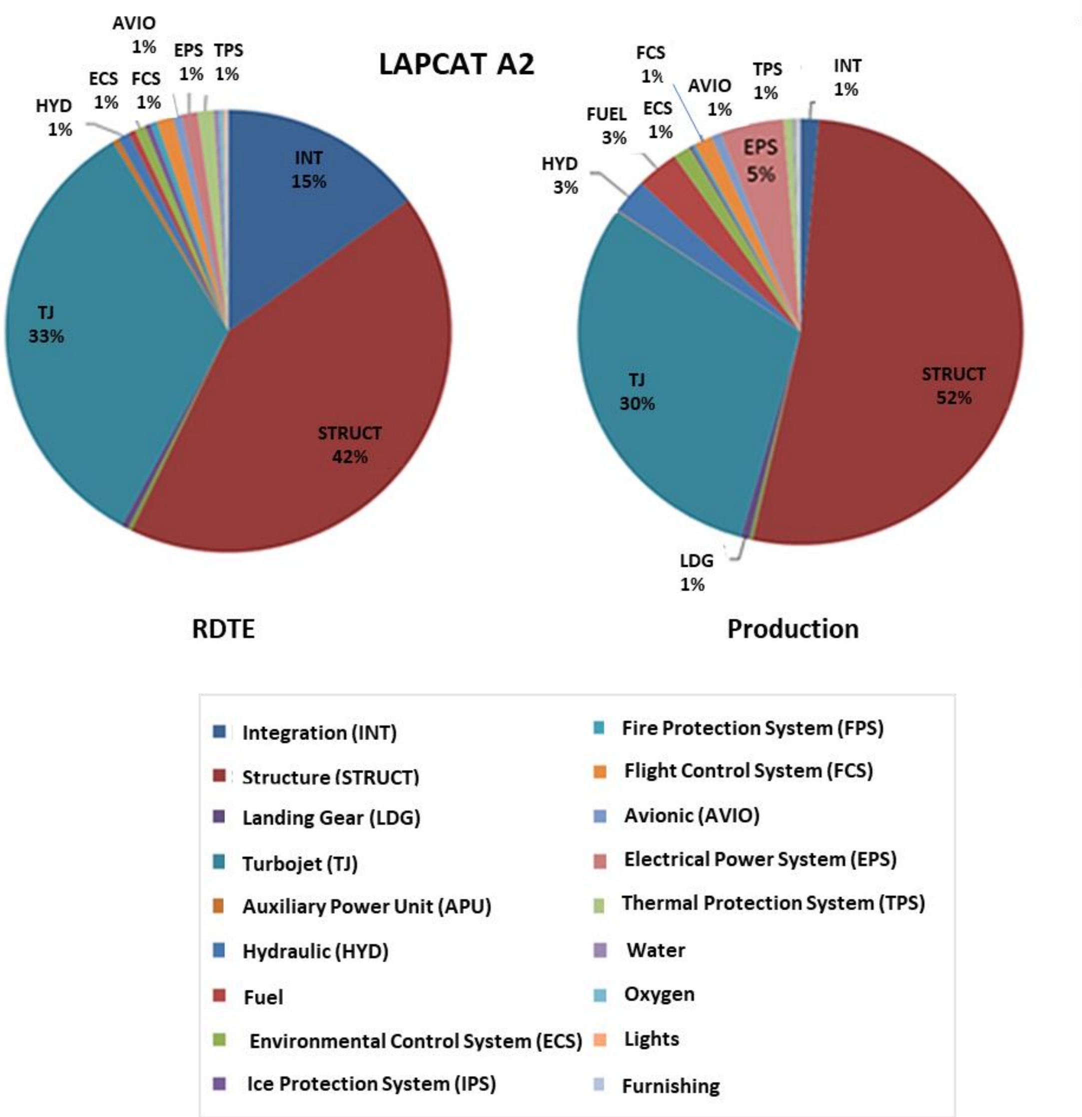

Fig 7. PBS costs allocation for LAPCAT A2

Other on-board subsystems complete the breakdown (Fig. 7 shows those which have an impact on cost greater than 1%). From the WBS perspective, it is clear how manufacturing activities have the most important contribution. This is mainly due to the recurring costs related to production (even if a portion of non-recurring costs is also present in manufacturing phase). Conceptual and detailed design (systems engineering and development respectively) cover the 17% of total cost, whilst other contributions come from project management, test campaigns and quality assurance.

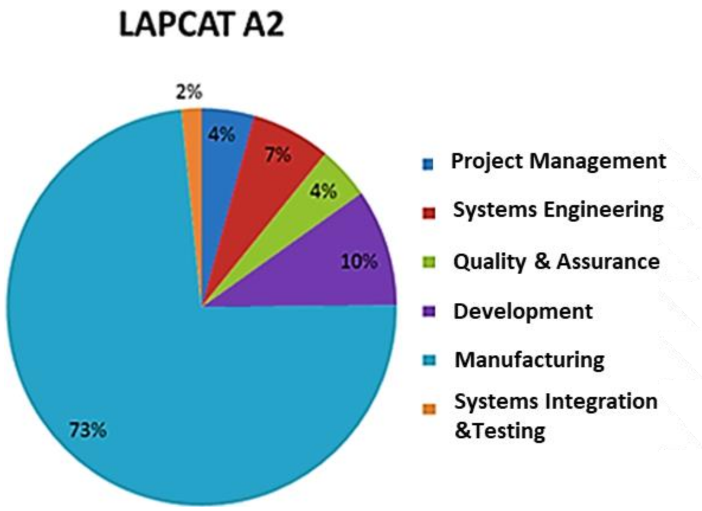

Fig 8. WBS costs allocation for LAPCAT A2

Considering DOC, the results are reported for both aircraft (LAPCAT A2 and MR2) and for both European Union (EU) and United States (US) scenarios (Table 6). It is specified that a fuel cost of 3.31 €/kg (1.7 $/lb) has been assumed for the US productive scenario, whilst 4.49 €/kg (2.3 $/lb) for the EU scenario [16]. Moreover, a depreciation life of 10 years and a 2% insurance rate are considered. Then, in a similar way, also indirect cost estimations have been included exploiting the guidelines from IATA [23] and ICAO [24] (see Table 7). It is specified that IOC results are valid for both the A2 and the MR2 configurations.

Table 6. DOC Results for A2 vehicle

Cost Item	**Definition**	**Cost, € FY2017/flight ($ FY2017/flight), EU scenario**	**Cost, €FY2017/flight ($ FY2017/flight), US scenario**
DOC_{Fuel}	Fuel Cost	818,339 (924,723)	604,859 (683,491)

DOC_{Crew}	Crew Cost	7711 (8713)	7711 (8713)
$DOC_{Insurance}$	Insurance Cost	9626 (10,877)	9626 (10,877)
$DOC_{Depreciation}$	Depreciation Cost	59,647 (67,401)	59,647 (67,401)
$DOC_{M/AF/L}$	Maintenance Cost (Airframe Labour)	3468 (3919)	3468 (3919)
$DOC_{M/AF/M}$	Maintenance Cost (Airframe Material)	6273 (7088)	6273 (7088)
$DOC_{M/E/L}$	Maintenance Cost (Engine Labour)	21,203 (23,959)	21,203 (23,959)
$DOC_{M/E/M}$	Maintenance Cost (Engine Material)	21,727 (24,551)	21,727 (24,551)
$DOC_{M,TOT}$	Total Maintenance Cost	52,671 (59,518)	52,671 (59,518)
Total DOC	Total Direct Operating Cost	947,994 (1,071,233)	734,514 (830,001)

Table 7. IOC Results for both A2 and MR2 vehicles

IOC Item	Value, € FY2017/flight ($ FY2017/flight)
Station and Ground	52,088 (58,859)
Traffic Service	3185 (3599)
Passenger Service	39,578 (44,723)
Reservation and Sales	43,029 (48,623)
General and Administrative	40,764 (46,063)
Aircraft Servicing	755 (853)
Airport Charges and Air Navigation Charges	46,992 (53,101)
Total	226,931 (256,432)

Table 8. Total Operating Cost for EU and US scenarios for LAPCAT A2

Cost Item	Cost, € FY2017/flight ($ FY2017/flight), EU scenario	Cost, € FY2017/flight, ($ FY2017/flight), US scenario
TOC	1,174,925 (1,327,665)	961,445 (1,086,433)

Eventually, Table 8 provides the Total Operating Cost (TOC) for the A2 vehicle derived from Table 6 and Table 7, considering both the EU and US LH_2 production scenarios. The detailed TOC breakdown for the EU scenario is shown in **Errore. L'origine riferimento non è stata trovata.**9.

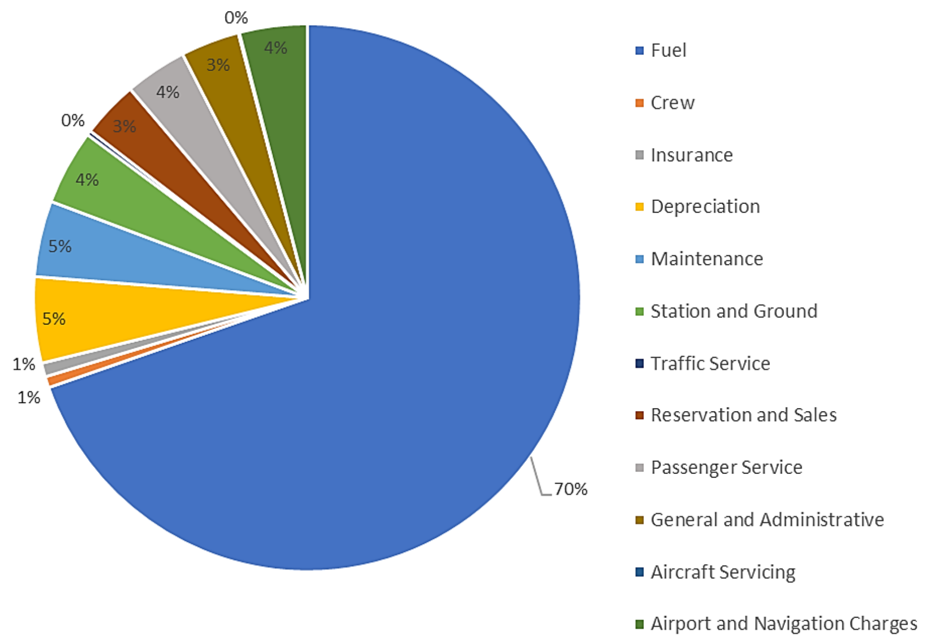

Fig 9. TOC cost breakdown for A2 cruiser

The estimations derived for LAPCAT MR2 [4,27,28] are herein presented in a similar way to what proposed for A2 vehicle. In this case, a reference was not available so the derived costs are reported in Table 9, Table 10 and Table 11 for RDTE and production costs (TFU and last unit respectively) as stand-alone.

Table 9. RDTE cost estimation for LAPCAT MR2

Cost Item (LAPCAT MR2)	**HyCost Model M€ FY2017 (M$ FY2017)**
ATR	5635 (6367)
DMR	1708 (1930)
Airframe	17,639 (19,932)
Vehicle	**24,982 (28230)**

Table 10. Production cost estimation for LAPCAT MR2 TFU

Cost Item (LAPCAT MR2)	HyCost Model M€ FY2017 (M$ FY2017)
ATR (average engine cost for TFU)	71 (80)
DMR	35 (39)
Airframe	940 (1062)
Vehicle	**1401 (1583)**

Table 11. Production cost estimation for LAPCAT MR2 200th unit produced

Cost Item (LAPCAT MR2)	HyCost Model M€ FY2017 (M$ FY2017)
ATR (average engine cost for 200th unit)	23 (26)
DMR	13 (15)
Airframe	189 (214)
Vehicle	**340 (384)**

The overall RDTE cost for MR2 (Table 9) is very similar to the one of the A2 (Table 3). Whereas the powerplant development is cheaper (Scimitar engine is more complex than the combination of Air Turbo Rocket (ATR) and Dual Model Ramjet (DMR) [29, 30, 31]), the RDTE airframe cost is instead higher due to the more complex configuration [32, 33].

The contributions of PBS and WBS items are shown in Fig. 10 and Fig. 11. As for the A2, the main RDTE items are structure and powerplant (both ATR and DMR).

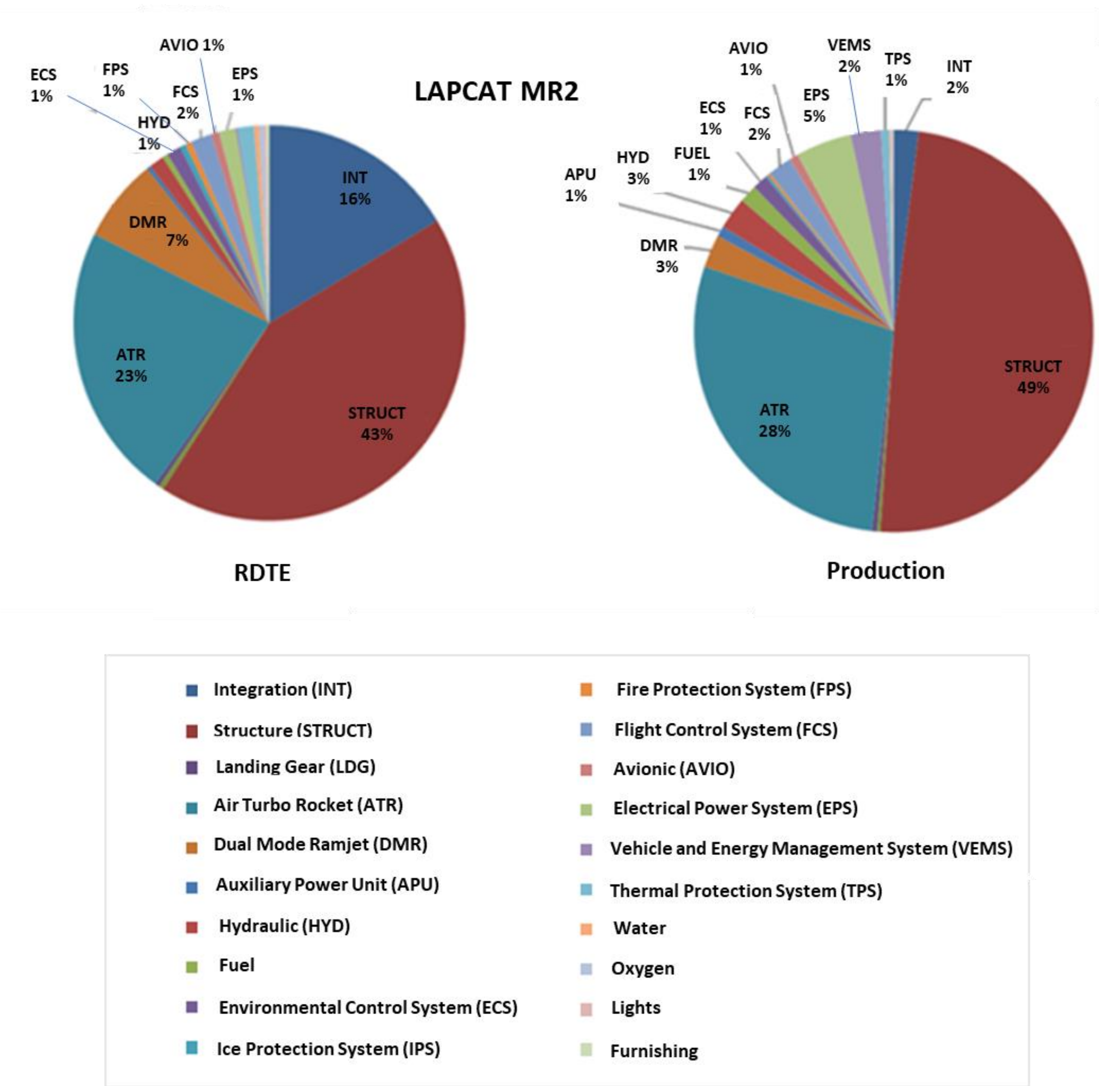

Fig 10. PBS costs allocation for LAPCAT MR2

Development cost of overall integration has a similar impact. There are no substantial differences in production costs breakdown, even if the Vehicle Energy Management System is here introduced [34]. WBS items are also in line with A2 estimations following this preliminary computation as shown in Fig.11. Table 12 summarizes the results concerning DOC estimation for LAPCAT MR2. Eventually, considering the IOC results reported in Table 7 and already assumed for the A2 vehicle, Table 13 summarizes the TOC for the MR2 vehicle considering both the EU and US LH_2 production scenarios.

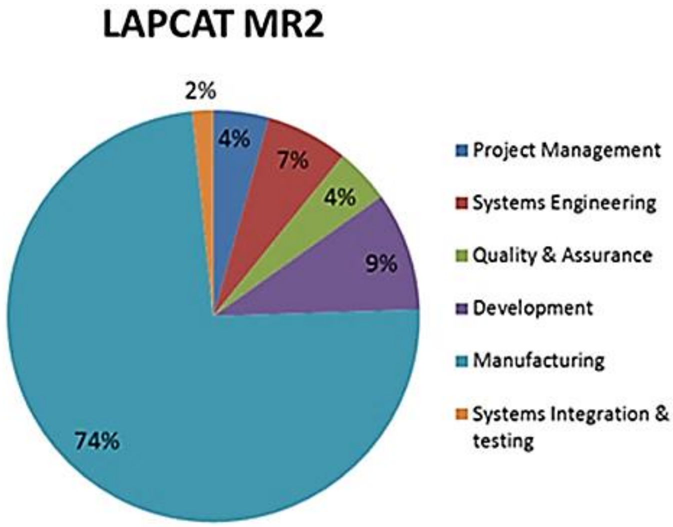

Fig 11. WBS costs allocation for LAPCAT MR2

Table 12. DOC Results for MR2 vehicle

Cost Item	Definition	Cost, € FY2017/flight ($ FY2017/flight), EU scenario	Cost, €2017/flight ($ FY2017/flight), US scenario
DOC_{Fuel}	Fuel Cost	626,881 (708,375)	463,346 (523,581)
DOC_{Crew}	Crew Cost	4849 (5479)	4849 (5479)
$DOC_{Insurance}$	Insurance Cost	10,433 (11789,29)	10,433 (11,789)
$DOC_{Depreciation}$	Depreciation Cost	64,088 (72,419)	64,088 (72,419)
$DOC_{M/AF/L}$	Maintenance Cost (Airframe Labour)	2856 (3227)	2856 (3227)
$DOC_{M/AF/M}$	Maintenance Cost (Airframe Material)	4488 (5071)	4488 (5071)
$DOC_{M/ATR/L}$	Maintenance Cost (ATR Engine Labour)	1227 (1386)	1227 (1386)
$DOC_{M/ATR/M}$	Maintenance Cost (ATR Engine Material)	10,191 (11,516)	10,191 (11,516)
$DOC_{M/DMR/L}$	Maintenance Cost (DMR Engine Labour)	1091 (1233)	1091 (1233)
$DOC_{M/DMR/M}$	Maintenance Cost (DMR Engine Material)	2044 (2310)	2044 (2310)
$DOC_{M,TOT}$	Total Maintenance Cost	21,897 (24,744)	21,897 (24,744)
Total DOC	Total Direct Operating Cost	**728,148 (822,807)**	**564,614 (638,013)**

Table 13. Total Operating Cost for EU and US scenarios for LAPCAT MR2

Cost Item	Cost, € FY2017/fli ght ($ FY2017/fli ght),	Cost, € FY2017/fli ght ($ FY2017/fli ght),

	EU scenario	US scenario
TOC	955,079 (1,079,239)	791,545 (894,446)

The two case studies reported in this section demonstrate the flexibility of the tool to tackle different vehicle configurations, providing reliable results. It is remarkable that the RDTE costs for the two configurations are close to each other. Besides the exploitation of two different propulsive strategies, the RDTE associated to the propulsive systems are very close as well, considering a similar degree of complexity for their development. The difference is due to the higher level of integration of the propulsive system (and in particular of its inlet [32]), within the airframe [25] [27] for the LAPCAT MR2.4 configuration [33]. Similar considerations apply for production costs. The introduction of a combined cycle as propulsive system for the LAPCAT A2 is the main reason for the cost increment as far as DOC is concerned. Indeed, the maintenance of the Scimitar engine can require additional time and expertise with respect to the maintenance actions of simpler turbojet and ramjet/scramjets.

IOC are not directly impacted by the vehicle configuration, but they are strictly related to operational scenario considered and the airline.

According to [35], the Ticket Price can now be estimated, imposing a certain profit margin that can be expressed as follows:

$$Profit = Ticket\ Revenue - (DOC + IOC) \tag{6}$$

where ticket revenue depends on the load factor (i.e. the ratio of the average payload carried to the maximum payload) and the pricing policies of the airline, i.e. the ticket price.

$$Ticket\ Price = \frac{Profit + (DOC + IOC)}{load\ factor} \tag{7}$$

Assuming a profit margin of about 10% of operating costs (7.7% plus fares) as suggested by IATA [36] and a load factor of 75%, the ticket prices in Table 14 are obtained.

From the preliminary ticket price results shown in Table 14 it can be noticed that the LAPCAT vehicles will be competitive with current business class tickets.

Table 14. Ticket Price for EU and US scenarios for LAPCAT A2 and MR2

	€2017/passenger $2017/passenger), per flight, EU scenario	**€2017/passenger ($2017/passenger), per flight, US scenario**

Ticket Price	LAPCAT A2	5744 (6491)	4700 (5311)
	LAPCAT MR2	4669 (5276)	3870 (4373)

6. Conclusions

This paper presents the methodology and tool developed by Politecnico di Torino and the European Space Agency for the Life Cycle Cost estimation of a high-speed transportation vehicle. The application of the methodology and tool to two different case studies (LAPCAT A2 and LAPCAT MR2.4 vehicle configurations) confirm the flexibility of both methodology and tool to provide proper cost estimations for two different high-speed vehicle configurations. Moreover, it is important to notice the possibility of assessing the impact of the different cost items onto the vehicle providing important feedbacks to the designers. For this reason, in future, this tool could be integrated within Concurrent Design Facilities which nowadays supports often many teams of researchers and engineers especially during the Conceptual and Preliminary Design phases. In future, both the methodology and the tool will be improved to allow the assessment of the impact of the introduction of new technologies onto the different cost items as well as onto the overall LCC of the vehicle.

Based on the various CER and cost items, the proposed methodology ends up with a single ticket price of 5744€ and 4669€ for FY2017 (considering the EU scenario), respectively for the LAPCAT A2 and MR2.4. These values are within current ticketing prices of business class travels.

7. Appendix I: Summary of TRANSCOST-modified CERs implemented in HyCost tool

7.1. RDTE Costs

Table 15. List of cost drivers for RDTE CERs

$C_{complexity}$	Complexity weighing factor for engines
C_{TOT}	Total RDTE cost [WYr]
f_0	Systems engineering integration factor (development)
f_1	Development standard factor
f_2	Technical quality factor
f_3	Team experience factor
f_6	Deviation from optimal schedule (delay factor)
f_7	Program organization factor
f_8	Region productivity factor
f'_{10}	Cost reduction factor
f_{11}	Reduction factor due to absence of government contracts
H_{CCE}	RDTE cost for Combined Cycle Engine [WYr]
H_{ER}	RDTE cost for ramjet engine [WYr]
H'_{ET}	RDTE cost for turbojet engine [WYr]
H_{VA}	RDTE cost for high speed advanced aircraft [WYr]
k_{TJ}	turbojet configuration coefficient (for engine characterization)
k_{RJ}	ramjet configuration coefficient (for engine characterization)
$M_{E_{dry}}$	Engine dry mass [kg]
M_{OEW}	Operating Empty Weight of the selected aircraft [kg]
$\dot{m}_{BO_{LH2}}$	Boil-off flow rate [kg/s]
P	Power produced by TEMS [W]
q	Heat flux [W/m^2]
$S_{Fuel_{dev}}$	RDTE cost for fuel system [WYr]
$S_{TEMS_{dev}}$	RDTE cost for TEMS [WYr]
$S_{TPS_{dev}}$	RDTE cost for TPS [WYr]
v	Aircraft flight speed (in cruise) [m/s]
n_E	Number of engine types installed

- **High Speed Advanced Aircraft**

$$H_{VA} = 2169 M_{OEW}^{0.262} f_1 f_2 f_3 f_8 f'_{10} f_{11}$$

- **Turbojet**

$$H'_{ET} = \left(232.4 {M_E}_{dry}^{0.509} + 1.12v\right) f_1 f_3$$

- **Ramjet**

$$H_{ER} = 355 {M_E}_{dry}^{0.295} f_1 f_3$$

- **Combined Cycle Engine**

$$H_{CCE} = C_{complexity}(k_{TJ} H'_{ET} + k_{RJ} H_{ER}) f_1 f_3$$

- **Fuel System**

$$S_{Fuel_{dev}} = \left(0.1 M_{OEW}^{0.68} + 0.49 {M_E}_{dry}^{0.51}\right) f_1 f_3$$

- **TPS**

$$S_{TPS_{dev}} = (0.56 M_{OEW}^{0.59} + 1.8 q^{0.51}) f_1 f_3$$

- **TEMS**

$$S_{TEMS_{dev}} = \left(5.73 M_{OEW}^{0.26} + 0.8 P^{0.17} + 0.53 \dot{m}_{BO}{}_{LH2}^{0.19}\right) f_1 f_3$$

- **Total Development Cost**

$$C_{TOT} = f_0 (H_{VA} + \sum_{i=1}^{n_E} H_{Ei}) f_6 f_7$$

7.2. Production Cost

Table 16. List of cost drivers for Production CERs

$C_{complexity}$	Complexity weighing factor for engines
C_F	Total Production cost [WYr]
F_{CCE}	Production cost for Combined Cycle Engine [WYr]
F_{ER}	Production cost for ramjet engine [WYr]
F'_{ET}	Production cost for turbojet engine [WYr]
F'_{VF}	Production cost for high speed advanced aircraft [WYr]
f'_0	Systems engineering integration factor (production)
f_4	Learning curve factor
f_9	Impact of subcontractors
f'_{10}	Cost reduction factor
k_{TJ}	turbojet configuration coefficient (for engine characterization)
k_{RJ}	ramjet configuration coefficient (for engine characterization)
$\dot{m}_{BO_{LH2}}$	Boil-off flow rate [kg/s]
$M_{E_{dry}}$	Engine dry mass [kg]
$M_{T_{OEW}}$	Operating Empty Weight of the selected aircraft [ton]
M_{OEW}	Operating Empty Weight of the selected aircraft [kg]
N	Number of vehicle stages
n	Number of vehicles produced
n_E	Number of engine types installed
n_e	Number of engines installed
P	Power produced by TEMS [W]
Q	Heat load [J/m2]
q	Heat flux [W/m2]
$S_{Fuel_{prod}}$	Production cost for fuel system [WYr]
$S_{TEMS_{prod}}$	Production cost for TEMS [WYr]
$S_{TPS_{prod}}$	Production cost for TPS [WYr]
T	Ramjet thrust [kN]
v	Aircraft flight speed (in cruise) [m/s]
v_k	Aircraft flight speed (in cruise) [km/h]

- **High Speed Advanced Aircraft**

$$F'_{VF} = \left(0.34 M_{T\,OEW}^{1.75} + 7.06 v_k^{0.4}\right) f'_{10}$$

- **Turbojet**

$$F'_{ET} = 2.29 M_{E\,dry}^{0.530} + 0.50 v^{0.60}$$

- **Ramjet**

$$F_{ER} = 5.63 T^{0.35}$$

- **Combined Cycle Engine**

$$F_{CCE} = C_{complexity}\left(k_{TJ} F'_{ET} + k_{RJ} F_{ER}\right)$$

- **Fuel System**

$$S_{Fuel_{prod}} = 0.48 M_{OEW}^{0.38} + 0.5 M_{E\,dry}^{0.39}$$

- **TPS**

$$S_{TPS_{prod}} = 0.51 M_{OEW}^{0.19} + 3.41 q^{0.12} + 0.68 Q^{0.11}$$

- **TEMS**

$$S_{TEMS_{prod}} = 5.41 M_{OEW}^{0.23} + 0.79 P^{0.15} + 0.52 \dot{m}_{BO\,LH2}^{0.19}$$

- **Total Production Cost**

$$C_F = f_0'^{N}\left(\sum_{i=1}^{n} F_{V_i} f_{4_i} + \sum_{j}^{n_e} F_{E_j} f_{4_j}\right) f_9$$

8. Appendix II: Summary of NASA-modified ATA CERs implemented in HyCost tool

8.1. Fuel Cost (DOC_f)

The fuel cost per ton-mile in SI units is:

$$\mathrm{DOC_{Fuel}} = \frac{1677.78\ \mathrm{C_f}\left(\frac{\mathrm{m_{fT}}}{\mathrm{m_{GTO}}}\right)(1 - \mathrm{K_R})}{(\mathrm{LF})\left(\frac{\mathrm{m_{PL}}}{\mathrm{m_{GTO}}}\right)\mathrm{R_T}}$$

Where:

- C_f is the cost of fuel per unit mass (in kg);
- m_{GTO} is the gross take-off mass;
- m_{PL} is the payload mass;
- K_R is the reserve fuel fraction [%].
- $\mathrm{R_T}$ is the range in km.

8.2. Crew Cost (DOC_C)

The crew cost per ton-mile in SI units is:

$$\mathrm{DOC_C} = \frac{\dfrac{320}{m_{GTO}}}{0.63(\mathrm{LF})\left(\dfrac{\mathrm{m_{PL}}}{m_{GTO}}\right)\mathrm{M}\left(\dfrac{\mathrm{V_B}}{\mathrm{V_{CR}}}\right)}$$

Where:

- V_{Cr} is the cruise speed;
- V_B is the block speed;
- M is the cruise Mach.

8.3. Insurance cost (DOC_I)

The insurance cost per ton-mile in SI units is:

$$\mathrm{DOC_I} = \frac{(\mathrm{IR})\left(\dfrac{\mathrm{C_{HST}}}{m_{\mathrm{GTO}}}\right)}{0.63(\mathrm{LF})\left(\dfrac{m_{\mathrm{PL}}}{m_{\mathrm{GTO}}}\right)\mathrm{M}\left(\dfrac{\mathrm{V_B}}{\mathrm{V_{CR}}}\right)\mathrm{U}}$$

Where:

- IR is the annual insurance rate;
- C_{HST} is the acquisition cost of the aircraft;
- U is the annual utilization in block hours/year.

8.4. Depreciation cost (DOC_D)

The depreciation cost per ton-mile in SI units is:

$$DOC_D = \frac{1.1\left(\dfrac{C_{HST}}{m_{GTO}}\right) + 0.3\left(\dfrac{C_{TJ}}{m_{GTO}} + \dfrac{C_{RJ}}{m_{GTO}}\right)}{0.63\ (\mathrm{LF})\left(\dfrac{m_{\mathrm{PL}}}{\mathrm{m_{GTO}}}\right)\mathrm{M}\left(\dfrac{\mathrm{V_B}}{\mathrm{V_{CR}}}\right)\mathrm{U\ L_d}}$$

Where:

- C_{TJ} is the cost of the turbojet engines;
- C_{RJ} cost of the ramjet engines.

8.5. Maintenance cost (DOCM)

Maintenance cost is given by the sum of labor and material cost for both airframe and engines. The NASA-Modified ATA CERs introduce the following four coefficients to estimate HST maintenance cost for labor and material of both turbojet and ramjet components:

- K_{LTJ}, turbojet maintenance labour ratio (HST turbojets to present subsonic turbojets);
- K_{MTJ}, turbojet maintenance material ratio (HST turbojets to present subsonic turbojets);
- K_{LRJ}, ramjet maintenance labor ratio (HST ramjets to present subsonic turbojets);
- K_{MRJ}, ramjet maintenance material ratio (HST ramjets to present subsonic turbojets).

The following six contributions shall be summed:

1. **$DOC_{M/AF/L}$,** maintenance labor effort required for the airframe (cost per ton-mile):

$$\mathrm{DOC_{M/AF/L}} = \frac{(3.70 + 2.18\, \mathrm{t_f}) \left[\frac{0.05}{1000} \left(\frac{\mathrm{m_{AF}}}{\mathrm{m_{GTO}}} + \frac{\mathrm{m_{AV}}}{\mathrm{m_{GTO}}} \right) + \left(\frac{3}{m_{GTO}} - \frac{315}{\left(\frac{2(m_{AF} + m_{AV})}{1000} + 120 \right) m_{GTO}} \right) \right] \mathrm{M}^{\frac{1}{2}}\, (\mathrm{r_L})}{(\mathrm{LF}) \left(\frac{m_{\mathrm{PL}}}{\mathrm{m_{GTO}}} \right) \frac{\mathrm{R_T}}{1000}}$$

Where:

- m_{AF} is the mass of airframe in kg,
- m_{AV} is the mass of avionics in kg,
- m_{GTO} is the maximum take-off mass in kg,
- r_L is the average labor rate per hour for all personnel involved in maintenance activities.

2. **$DOC_{M/AF/M}$,** maintenance material cost for the airframe (cost per ton-mile):

$$\mathrm{DOC_{M/AF/M}} = \frac{(5.22 \cdot \mathrm{t_f} + 10.57) \left(\frac{\mathrm{C_{HST}}}{\mathrm{m_{GTO}}} - \frac{\mathrm{C_{TJ}}}{\mathrm{m_{GTO}}} - \frac{\mathrm{C_{RJ}}}{\mathrm{m_{GTO}}} \right)}{(\mathrm{LF}) \left(\frac{\mathrm{m_{PL}}}{\mathrm{m_{GTO}}} \right) \mathrm{R_T} \cdot 10^3}$$

3. **$DOC_{M/TJ/L}$,** Maintenance labor effort required for the turbojet engines (cost per ton-mile):

$$\mathrm{DOC_{M/TJ/L}} = \frac{\left(\frac{\mathrm{T}}{\mathrm{W}} \right)_{\mathrm{GTO}} \left(1 + k_{TJ} \cdot\ \mathrm{t_F} \right) \left(\frac{9.91}{\mathrm{T_{TJ}}/10^3} + 0.1 \right) \mathrm{r_L\, K_{LTJ}}}{(\mathrm{LF}) \left(\frac{\mathrm{m_{PL}}}{\mathrm{m_{GTO}}} \right) \mathrm{R_T}}$$

Where:

- T_{TJ} is the thrust of each turbojet engine in N;
- t_F is the number of flight hours per flight;
- k_{TJ} is the time of operation of the turbojet engines as a ratio of t_F.

4. **$DOC_{M/TJ/M}$,** the maintenance material required for the turbojet engines (cost per ton-mile).

$$\mathrm{DOC_{M/TJ/M}} = \frac{\left(\frac{\mathrm{C_{TJ}}}{\mathrm{m_{GTO}}} \right) \left(0.034 \cdot k_{TJ} \cdot\ \mathrm{t_F} + 0.042 \right) \mathrm{K_{MTJ}}}{(\mathrm{LF}) \left(\frac{\mathrm{m_{PL}}}{\mathrm{m_{GTO}}} \right) \mathrm{R_T}}$$

5. **$DOC_{M/RJ/L}$,** the maintenance labor required for the ramjet engines (cost per ton-mile):

$$\mathrm{DOC_{M/RJ/L}} = \frac{\left(1 + k_{RJ} \cdot \mathrm{t_F} \right) \left(\frac{1.01\ \mathrm{N_{RJ}} \left(\frac{\mathrm{L}}{\mathrm{D}} \right)}{\mathrm{m_{GTO}}/\ 10^3} + 0.1 \right) \mathrm{r_L\, K_{LRJ}}}{\left(\frac{\mathrm{L}}{\mathrm{D}} \right) (\mathrm{LF}) \left(\frac{m_{\mathrm{PL}}}{\mathrm{m_{GTO}}} \right) \mathrm{R_T}}$$

Where $\frac{L}{D}$ is the lift-to-drag ratio.

6. **DOC$_{M/RJ/M}$,** the maintenance material cost for ramjet engines (cost per ton-mile):

$$\mathrm{DOC_{M/RJ/M}} = \frac{\left(\frac{\mathrm{C_{RJ}}}{\mathrm{m_{GTO}}}\right)\left(0.034 \cdot k_{RJ} \cdot \mathrm{t_F} + 0.042\right) \mathrm{K_{MRJ}}}{(\mathrm{LF})\left(\frac{\mathrm{m_{PL}}}{\mathrm{m_{GTO}}}\right) \mathrm{R_T}}$$

9. Appendix III: HyCost Tool Screenshots

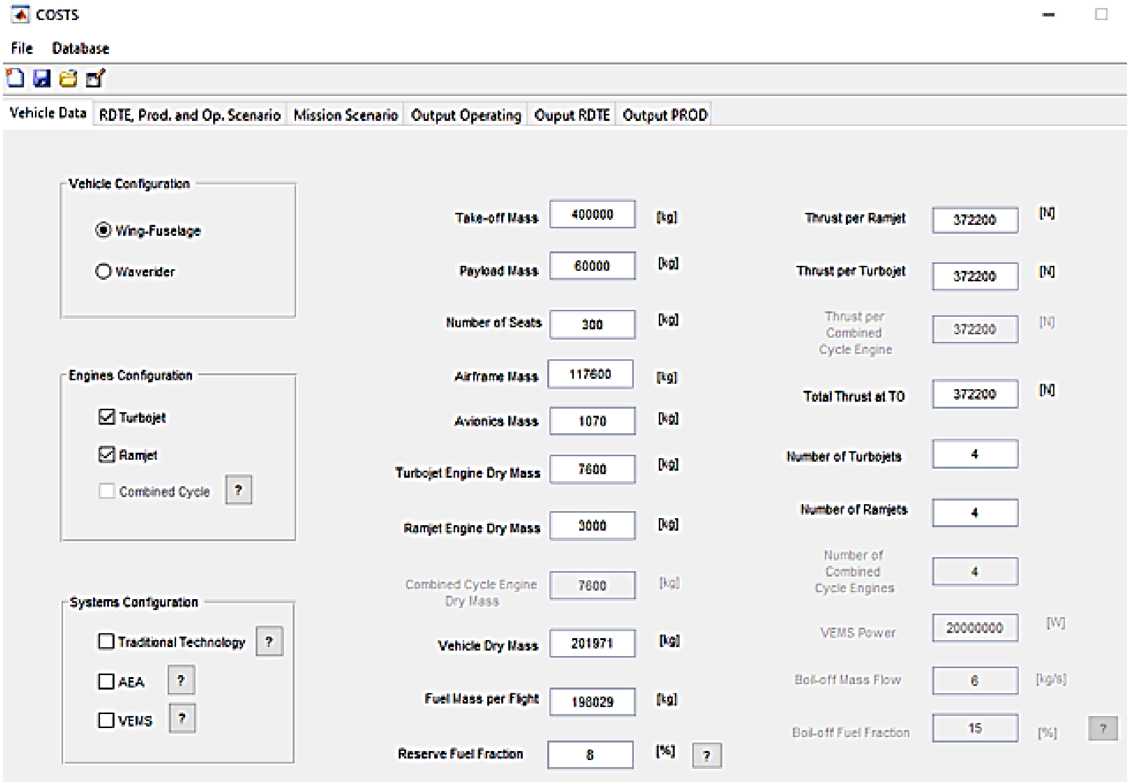

Fig 12. Example of HyCost input windows: vehicle and mission data

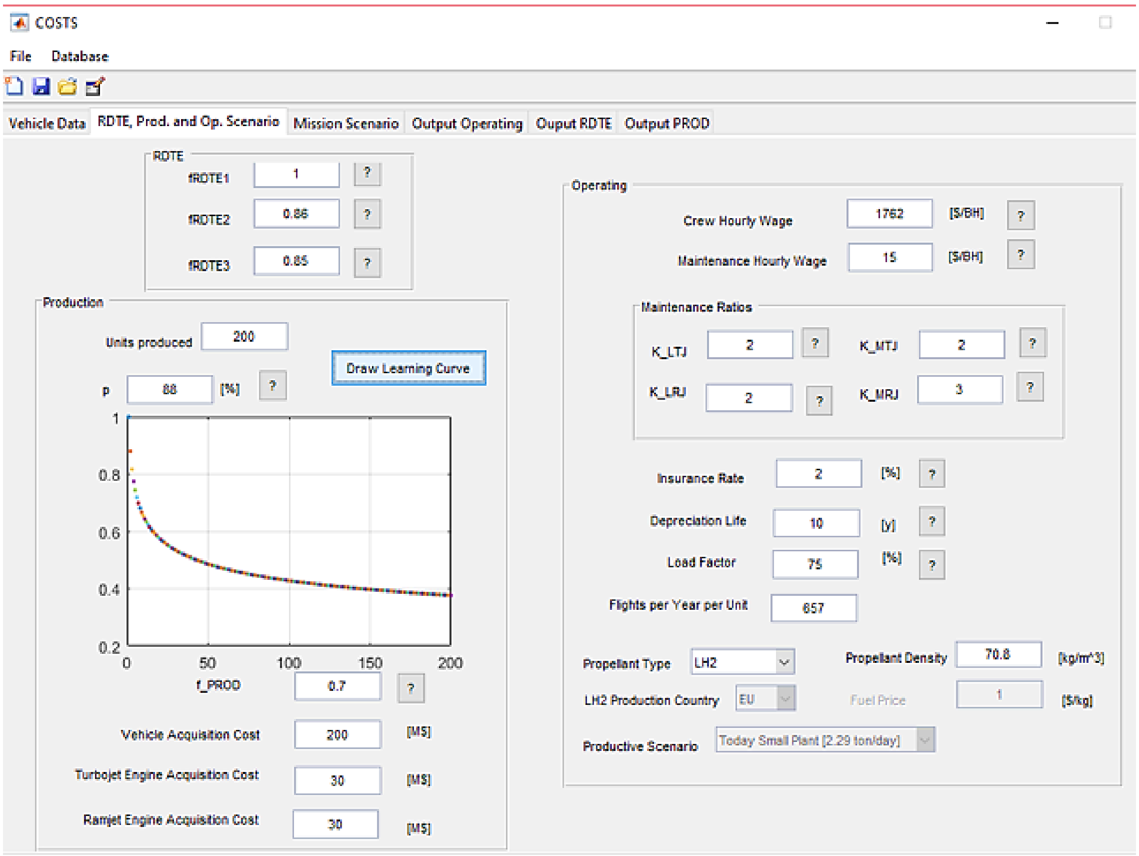

Fig 13. Example of HyCost input windows: development, production and operating scenario

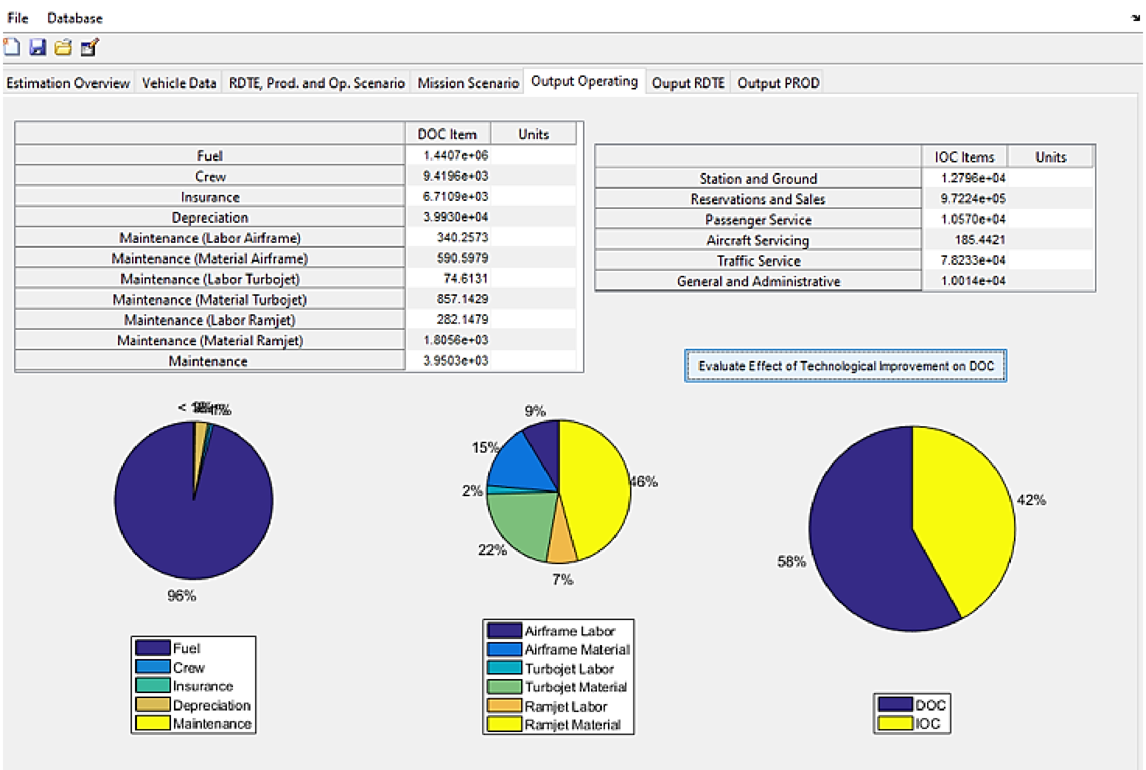

Fig 14. Example of HyCost DOC output window

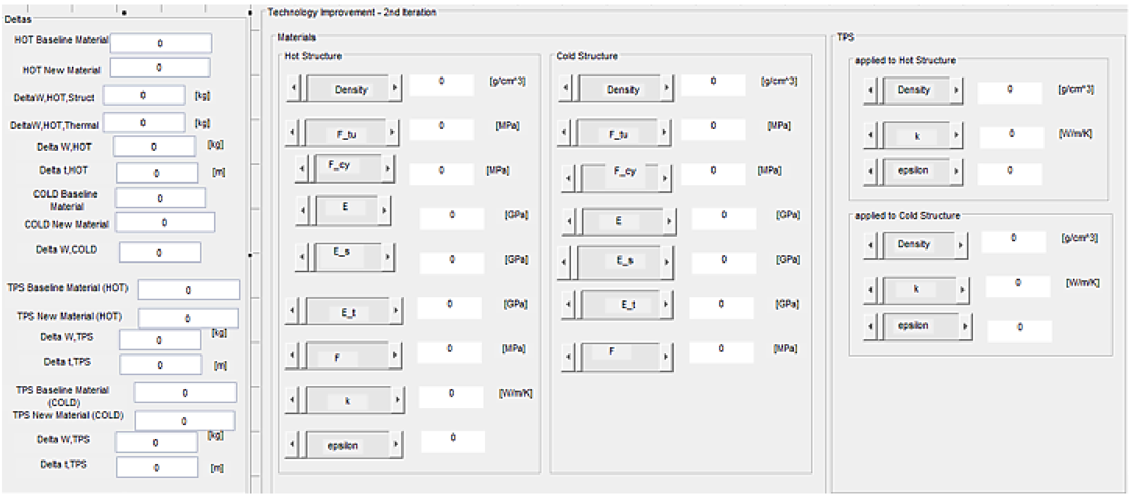

Fig 15. HyCost window for the evaluation of technological improvements

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