Life cycle cost estimation methodology for hypersonic transportation systems

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LIFE CYCLE COST ESTIMATION METHODOLOGY FOR HYPERSONIC TRANSPORTATION SYSTEMS

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Abstract

In this last decade, both the aeronautical and aerospace domains are looking with special interest towards the development of hypersonic transportation systems with different purposes. Indeed, considering the specific technologies that have been installed on-board, the vehicle can allow performing recurrent access to space (with reusable vehicles), suborbital parabolic flights with commercial or scientific purposes or point-to-point connections. In order to enhance the competitiveness of the project, cost analyses should be carried out since the very beginning of the design process taking into account not only Research & Development Costs and Production Costs, but also the Operating Costs. The lack of cost models for the segment of reusable high-speed vehicles is a problem in estimating the total effort from design, production up to exploitation. The formalization of a dedicated model for the estimation of development, production and operative costs of reusable transportation vehicles is therefore a crucial need. In this context, the proposed work deals with the generation of a parametric cost estimation tool, which consists of several Cost Estimation Relationships (CERs) for the overall reusability development, production and operating costs. The derived model is exploited to perform a preliminary cost assessment for the main vehicles designed within the LAPCAT (Long-Term Advanced Propulsion Concepts and Technologies) projects.

1 Introduction

Costs may represent one of the hampering factors towards a future generation of high-speed transportation systems and it is fundamental to assess the overall Life Cycle Cost (LCC) of aircraft since the very beginning of the design process. This means that, especially for this new kind of innovative transportation systems, it is not only important to estimate their acquisition cost but also to determine the expenses incurred during aircraft operations. For this reason, this paper presents a methodology specifically developed for high-speed transportation systems, where traditional approaches, mainly based on statistical trends, cannot be applied (at least in their original formulation) due to the lack of data about real missions. The accuracy of the model has been verified through the application of the entire methodology to the LCC of the LAPCAT A2, a hypersonic point-to-point vehicle concept, for which, a preliminary analysis has already been carried out by Reaction Engines Limited (REL). Thus, Section 2 briefly describes the vehicle used for validation (LAPCAT A2) and the LAPCAT MR2 used as major case study. In addition, this section also briefly summarizes the already available cost estimation results for the LAPCAT A2 model. Then, Section 3 describes the methodology developed for LCC estimation of high-speed transportation systems, providing some details about the estimation models for Research, Development, Test and Evaluation (RDTE), Production as well as for Operating Costs. Consequently, Section 4 reports the main results from the application of the methodology to both LAPCAT A2 and LAPCAT MR2 concepts, allowing the reader to appreciate how the developed methodology is sensitive to different configurations and technologies. Eventually, Section 5 highlights the main conclusions and it gives some ideas for future works.

2 Reference case studies: LAPCAT A2 and LAPCAT MR2

2.1 Vehicle data

LAPCAT was an EU Project coordinated by European Space Agency (ESA) and funded for two consecutive editions (LAPCAT and LAPCAT II) from 2005 to 2013 [1], [2]. The main goal was to perform the preliminary design of a suitable hypersonic cruiser concept over iterative design loops. Different aircraft configurations were proposed and trade studies were conducted to choose the best platform architecture. In this section, the features of the two main concepts from LAPCAT and LAPCAT II studies are briefly introduced.

The LAPCAT A2 (Fig. 1) is a Mach 5 vehicle, designed to perform antipodal flights (>16000 km). The A2 presents a conventional wing-body configuration. Its fuselage consists of an external aeroshell (reinforced with ceramic composite materials), insulation, actively cooled screen, structure in carbon fiber reinforced polymer (CFRP), and hydrogen tankage in welded aluminum. Furthermore, it is equipped with four Scimitar precooled engines [1]. The Scimitar engine is a derivative of the Sabre spaceplane engine, which is intended for SSTO launcher application, but designed to a longer life. It is based on existing gas turbine, rocket, and subsonic ramjet technology. The aircraft has a Maximum Take-Off Weight (MTOW) of about 400 tons for a maximum seating capacity of 300 passengers.

Fig. 1 LAPCAT A2 Hypersonic Cruiser

The LAPCAT MR2 vehicle (Fig. 2) is a waverider configuration equipped with six Air Turbo Rocket (ATR) and one Dual Mode Ramjet (DMR), which allow reaching Mach 8 at an altitude around 33000 m. [4]. The engines use liquid hydrogen (LH2) as fuel and take ram-air from a central intake which is equipped with several ramps that can be moved to drive the airflow either to the ATR or to the DMR depending on the flight conditions. Notably, the six ATR operate up to Mach 4-4.5, whilst the DMR is used for hypersonic flight from Mach 4.5 up to Mach 8. The vehicle is conceived to host 300 passengers providing a commercial antipodal flight service (comparable to those specified for A2) across the globe and it is characterized by a MTOW of about 400 tons.

Fig. 2 LAPCAT MR2 Hypersonic Cruiser [4]

2.2 RDTE, Prod and operating scenario

An overall scenario concerning development, production and operating program shall be established in order to perform a LCC estimation for the selected vehicles. Moreover, it is important to use the same assumptions for both vehicles to consider a fair comparison of the results. An overall development program of 13 years is suggested by REL (from conceptual design to certification) for this kind of vehicle so it is reasonable to stay close to this value. This means that the hypothesized Entry Into Service (EIS) is expected between 2030 and 2031. However, cost estimations are performed with 2017 currency. A proper exponential learning curve function is used to consider production cost reduction, with a reference value of 15% of cost decrease every time the number of units doubles (residual production cost is then 85%). An overall production run of 200 vehicles is considered.

2.3 Mission scenario

LAPCAT A2 and LAPCAT MR2 are two different vehicle concepts both aiming to a similar mission: connecting antipodal locations flying at very high-speed (Mach 5 and Mach 8 respectively). They will operate from a selected set of airport able to fulfill their take-off and landing requirements and they will reach high altitudes to perform the high-speed cruise. As example, the mission profile of LAPCAT MR2 is reported in Fig. 3 where altitude and Mach trends are shown as function of mission time.

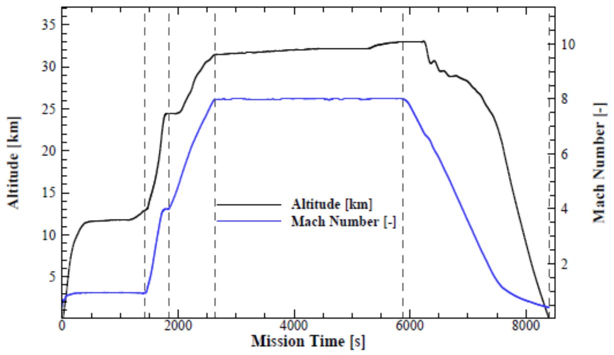

Fig. 3 Reference mission for LAPCAT MR2 [13]

The LAPCAT vehicles are expected to carry about 148,000 passengers per year performing 2 flights per day with 90% availability and a 75% load factor (i.e. the ratio of the average payload carried to the maximum payload).

2.4 Reference cost model (by REL)

As it has been anticipated in the introduction, previous cost estimations for LAPCAT A2 have already been assessed by Reaction Engine Limited (REL). Besides high-level granularity of the estimation, these results have been properly exploited to tune some numerical parameters of the developed semi-empirical models as well as to validate the entire methodology. Table 1 shows the main results in terms of RDTE and production costs of this reference study. Values are represented in 2006 Euro (€) currency. The analysis from REL considered a lower production run if compared to the one described in this study, limiting the number of vehicles built to 100 units.

Cost Item (LAPCAT A2)	RDTE Cost [M€]	Production Cost TFU [M€]	Production Cost Average [M€]
Scimitar	8,147	81	26
Airframe	14,454	712	310
Vehicle	**22,601**	**979**	**413**

Table 1 RDTE and production costs for A2 vehicle as from REL for year 2006

Theoretical First Unit (TFU) cost for engine and airframe refers to the very first unit built, whilst the vehicle TFU is derived considering both contributions and applying a learning curve function to the engine cost (there are four Scimitar engines for each vehicle thus the engine cost decreases faster over the production since the number of engines built is four times the airframes). The average cost is computed considering 100 vehicle units (400 engines). Concerning operating costs, Table 2 gathers the annual operating expenses for the A2 cruiser, reporting Direct and Indirect Operating Costs (DOC and IOC, including flight crew costs) and Total Operating Cost (TOC), given by the sum of DOC and IOC. *Aircraft Cost* includes both depreciation and interest costs. For fuel cost, a price of 3.5 €/kg is assumed.

Operating Cost Item	Annual Cost, [M€]
Aircraft cost	46
Maintenance	21
Fuel	460
Total DOC	527
Total IOC (including flight crew)	26.8
TOC	553.8

Table 2 TOC breakdown as from REL for A2 vehicle (reference year 2006)

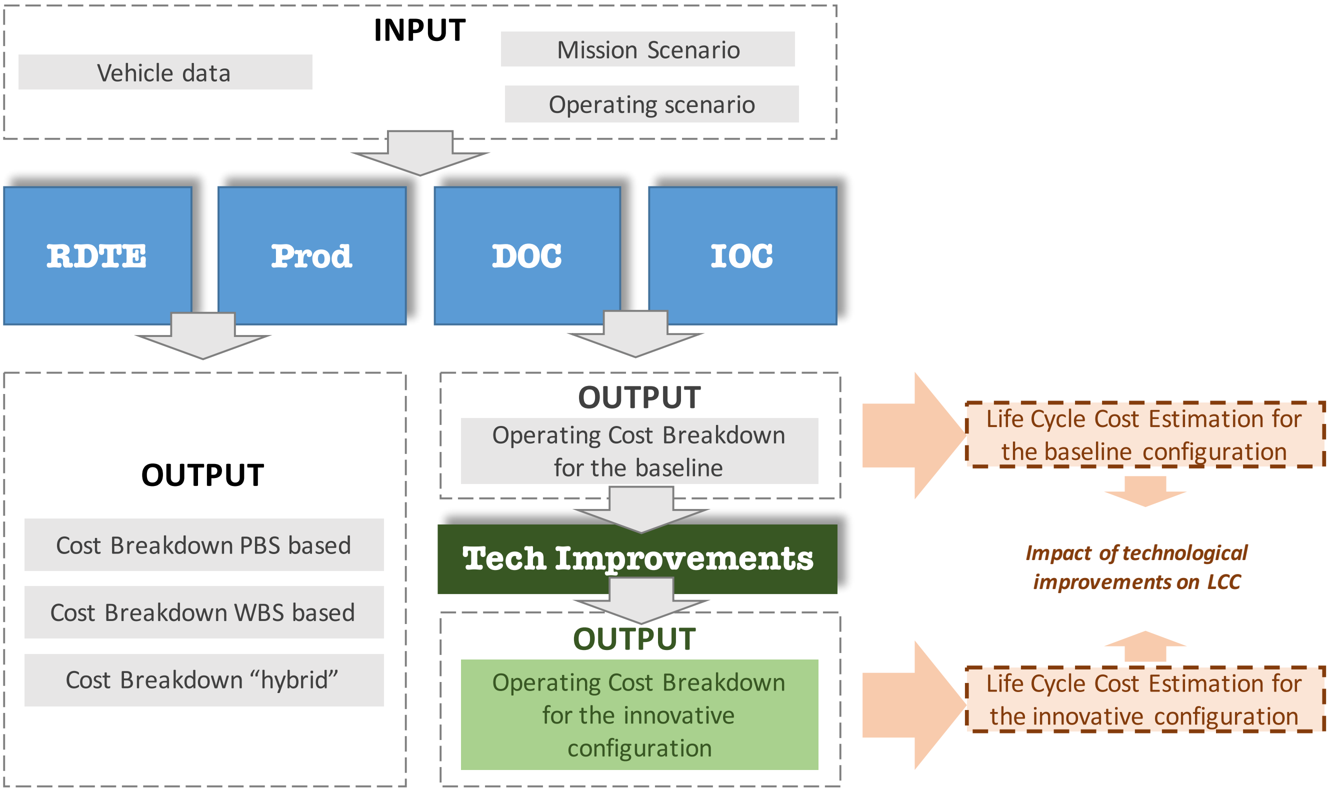

Fig. 4 Flowchart of the methodology for hypersonic cruisers LCC assessment

3 Life Cycle Cost Estimation Methodology

This section aims at providing an overview of the methodology developed by Politecnico di Torino with the support of ESA, to perform LCC assessment during conceptual design level for breakthrough innovative high-speed transportation systems. summarizes the main bricks of the developed methodology. The level of detail of the required input data are basically described in Section 2, where the case studies are described. As indicated, depending on the specific subroutines, only subsets of input data are requested. The overall methodology encompasses four different cost models allowing the estimation of RDTE,
Production, DOC and IOC. Then a fifth additional model is devoted to the estimation of the impact of technological improvements onto costs. This paper describes and provides the results for the core models while the estimation refinement routines will be in-depth presented in future publications.

3.1 RDTE and Production Costs Estimation

Besides different models for RDTE costs are currently available in literature, since the beginning of this research activity it has been evident that it was not possible to fully rely on them, because of the high level of innovation to be considered. Indeed, also the exploitation of existing commercial tools, like for example the True Planning software by Price Systems, provides non reliable costs estimations for breakthrough innovative vehicle and subsystems. Indeed, the models already implemented within these cost estimation routines provides plausible results only for inputs laying within specific boundary conditions. In the case of hypersonic transportation systems, many subsystems (e.g. the propulsion system, the thermal and energy management subsystem, etc.) are characterized by performances well outside these boundaries and the results obtained for the LAPCAT A2 were far from REL expectations.
Thus, the authors committed themselves developing a new cost model consisting in a set of mathematical equations called CERs (Cost Estimation Relationships) for the RDTE and Production cost for high-speed transportation

systems. The process leading to the final model derivation is reported schematically in Fig. 5
The starting point of the methodology for the RDTE and Production cost estimation is the definition of the items for which there is an interest in performing the cost evaluation. In particular, three different cost breakdowns have been evaluated during this research activity:

- Cost Breakdown following the Product Breakdown Structure (PBS)
- Cost Breakdown following the Work Breakdown Structure (WBS)
- Hybrid Breakdown mapping PBS onto WBS

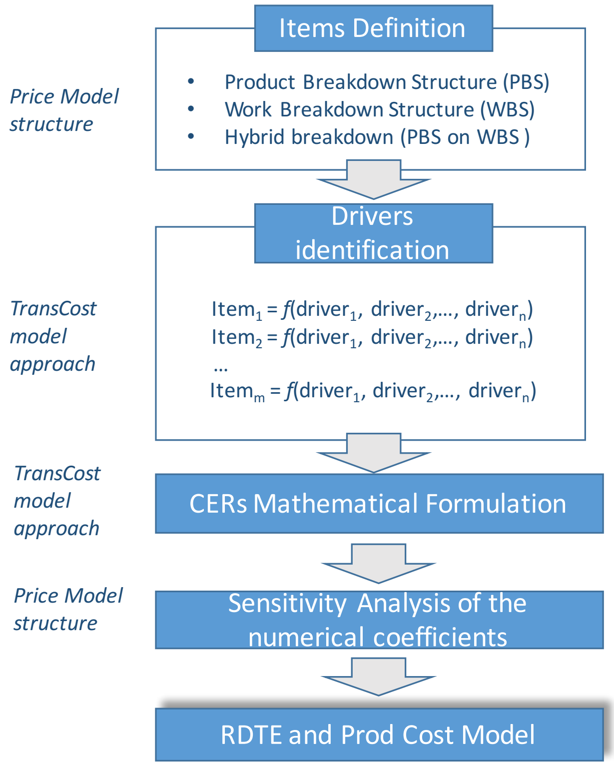

Fig. 5 Flowchart for the development of the methodology for RDTE and production costs

In this case, commercial software, like True Planning by Price Systems could help suggesting some baselines for the breakdowns. However, the list of items is a peculiarity of each vehicle, and thus, it is one of the required input data.
Then, once the items list had been derived, it has been necessary to identify the group of drivers having an impact on each specific cost item. This is a preliminary activity towards the definition of precise mathematical formulations in which each item is a function of several drivers. In this case, the formulations suggested by TransCost [5] have been considered as a starting point and they have been modified in order to be applicable to high-speed transportation systems and breakthrough innovative technologies. Thus, depending on the item under investigation, the original formulation has been slightly or deeply modified, adding, for example, new drivers. Then, before being able to provide the final formulation, it has been necessary to perform a sensitivity analysis of the results with the final scope of tuning the numerical coefficients of the formulation in order to make the model able to predict the cost estimation for our case studies.

3.2.1 Example: RDTE CER for airbreathing engine

For the sake of clarity, the example of the airbreathing engine development CER is reported in this section. Airbreathing engine is one of the most critical subsystems of our selected test case and, in general, of a high-speed transportation system. Moreover, it is one of the item of the PBS. The TransCost development CER related to airbreathing engines uses as only driver dry mass but this approximation may lead to bad correlations at high Mach numbers. Thus, the model developed by PoliTO, suggests a modified equation, where also vehicle speed is included as driver. The final suggested CER for turbojet engine (TJ) is:

$$(C_{RDTE})_{TJ} = \left(232.4 {M_E}_{dry}^{0.509} + 1.12v\right) f_1 f_3 \quad (1)$$

where:

- ${M_E}_{dry}$ is the engine dry mass [kg]
- v is the flight speed in $[m/s]$
- f_1 is the development standard factor as used in TransCost (it indicates the development effort compared to state-of-art projects)
- f_3 is the team experience factor as used in TransCost

From Fig. 6 and Fig. 7, it is possible to see how the new trend better suits the innovative propulsive configurations, even if it provides reliable results only for engine dry masses higher than 1000 kg. Considering the propulsive performances required by high-speed transportation systems, the engine dry mass has always a higher impact on the related cost.

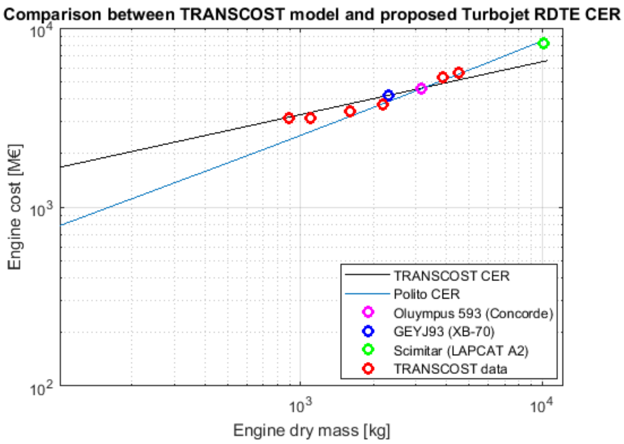

Fig. 6 Comparison between TransCost model and proposed CER for turbojet engine RDTE cost

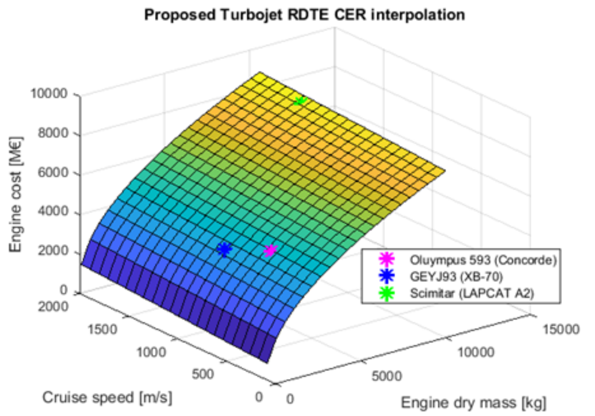

Fig. 7 Proposed Turbojet RDTE CER (3D plot)

However, it is difficult to evaluate more specific powerplant solutions exploiting, for example, combined cycle engines like turboramjets, and innovative propulsion concepts (like the Scimitar). An average solution relies on the evaluation of the cost by exploiting a mixed formulation reported

$$(C_{RDTE})_{CCE} = C_{complexity}(k_{TJ}C_{RDTE_{TJ}} + k_{RJ}C_{RDTE_{RJ}})f_1 f_3 \quad (2)$$

where:

- $C_{complexity}$ is a multiplication factor used to compare the considered design to an existing one (this is used to tune the level of complexity of the selected engine)
- k_{TJ} and k_{RJ} are the turbojet and ramjet configuration coefficients used to represent the characteristics of the engine (i.e. if it is closer either to a turbojet or to a ramjet), ranging from 0 to 1 (e.g. $k_{TJ} = 0.6, k_{RJ} = 0.4$).
- $C_{RDTE_{TJ}}$ and $C_{RDTE_{RJ}}$ are RDTE costs of turbojet and ramjet

Fig. 8 compares the trends of equation (1) and **Errore. L'origine riferimento non è stata trovata.**, considering in this case a $C_{complexity} = 1$ and an equal contribution (0.5) of turbojet and ramjet configurations, with original airbreathing engines RDTE cost estimations proposed by TransCost [5].

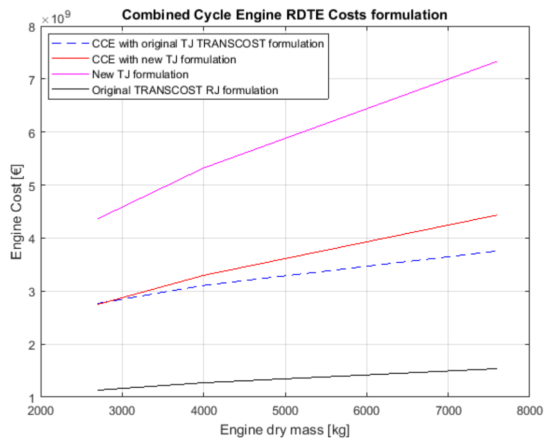

Fig. 8 Combined Cycle Engine RDTE cost formulation

3.2 Direct Operating Costs Estimation

Considering DOC, the approach followed is quite similar to the one described for the RDTE and production cost estimation. In his case, a modified version of the CERs proposed by Air Transport Association (ATA) in [6] suggested by NASA [7] has been taken as reference, but again, special effort has been devoted to the identification of additional drivers to be used to make the model applicable to all our case studies. In particular, the diagram in Fig. 9 reports all the cost items that have been selected for the DOC estimation. As shown in the flowchart (see), the starting point of this analysis is the definition of the mission that the vehicle would perform. Though high-speed transportation systems may be also exploited to perform parabolic flights as well as for reusable access to space, in this paper the authors focus on point-to-point cruisers. In this case, the mission should be defined in terms of maximum reachable altitude, time of flight, maximum Mach number and, in case of multi-modes propulsion system, it is necessary to specify the percentage of time with respect to the overall flight time of each mode of operation of the subsystem. Then, it is also important to describe the main characteristics of the operating scenario, specifying the number of flights per year that are envisaged for each aircraft as well as the type and the amount of fuel. Indeed, as it is reported in many reference documents, the most important item of DOC is fuel. Considering that most of the concepts currently investigated are fueled with liquid hydrogen, special attention has been devoted to the estimation of fuel price with respect to the productive scenario. Making benefits of some works available in literature [8], [9]the formulation suggested by TransCost [5] has been modified in order to consider different types of productive scenarios i.e. from the current scenario to a future one with a continuous production of LH2 in a wide numbers of plants, thanks to the maturation of some enabling technologies.

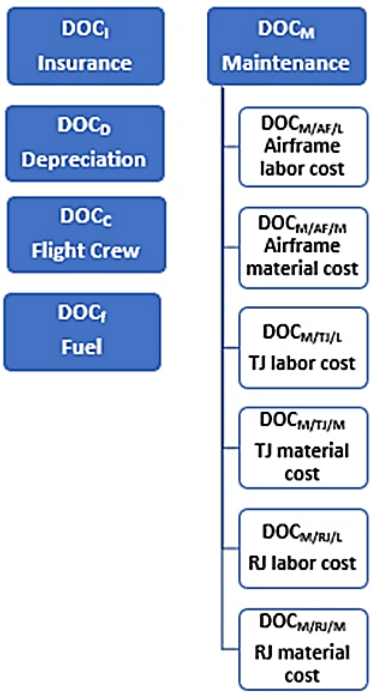

Fig. 9 Analyzed DOC items

Then, for each of the items reported in Fig. 9, a proper formulation has been set up, including different drivers with respect to the original formulation or simply explicating some already present variables as function of other parameters. In a similar way with respect to the process described in the previous section, the final DOC CERs formulation have been provided after an in-depth investigation and tuning of the numerical parameters.

3.2.1 Example: CER for fuel cost assessment

Considering the importance of fuel expenses estimation, this explanatory example has been dedicated to this item. The final formulation is the following:

$$DOC_{Fuel} = C_f \, m_{fT}(1 - K_R - K_B) \qquad (2)$$

where:

- DOC_{Fuel} is the DOC of fuel
- C_f is the cost of fuel;
- m_{fT} is the fuel mass per flight;
- K_R is the reserve fuel fraction which may be 8% of m_{fT};
- K_B is the boil-off fuel fraction. For more details of boil-off on hypersonic cruisers see [10].

In Eq. (2) the most important driver is C_f , which can be affected by:

- Geographical context where LH2 is produced: there is a clear difference between USA and EU scenarios, mainly due to the cost of the energy. As stated in TransCost [5], the LH2 produced in Europe can be twice as expensive as in USA due to different costs of the electrical energy.
- Daily production rate: the LH2 production rate per day is strongly affecting the LH2 costs as clearly confirmed in different references (see [5] and [8]).
- Production process: to assess LH2 cost per kg to estimate the operating costs for a hypersonic vehicle, the final product cost is given by the sum of all the costs incurred during the production process. phases, i.e. (i) the gaseous hydrogen extraction (in this case, the production by means of electrolysis has been considered) and (ii) the subsequent liquefaction.

The model developed by PoliTO during this research activity allows making a more realistic estimation of the LH2 productive scenarios, guaranteeing a higher competitivity to these vehicle configurations. Fig. 10 shows LH2 cost for different productive scenarios (EU and US) compared to TransCost (TC) data.

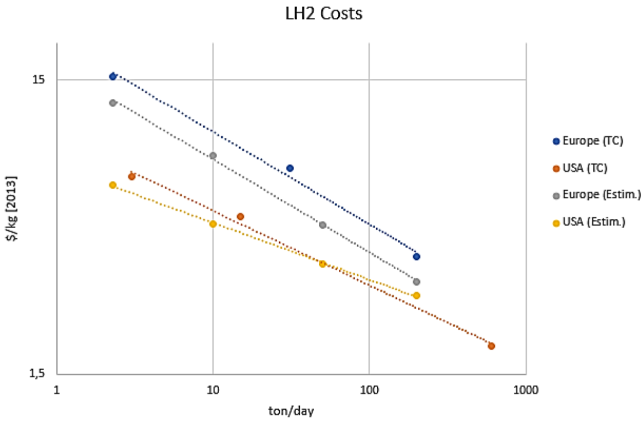

Fig. 10 LH2 production cost for EU and US scenarios

3.3 Indirect Operating Costs Estimation

The indirect operating costs are usually neglected especially during conceptual design cost assessment, but they should be absolutely taken into account if a reliable estimation has to be pursued.

Cost Item	Source
General and Administrative	IATA [11]
Reservation, Ticketing, Sales and Promotion	IATA [11]
Station and Ground	IATA [11]
Airport Charges and Air Navigation Charges	IATA [11]
Passenger Service and Cabin Attendants	IATA [11] ICAO [12]
Aircraft Servicing Costs	ICAO [12]
Traffic Servicing Costs	ICAO [12]

Table 3. Summary of IOC cost items and related references

In this case, the analysis performed by the authors leads to the conclusion that this type of costs are not affected by the type of aircraft configuration or mission, thus typical aeronautical breakdown and formulations could be applied. In particular, the following Table 3 summarizes the major cost items and references suggested for the evaluation of each item.

4. Results

4.1 LAPCAT A2 LCC estimation

Considering the RDTE and Production costs, a cost breakdown up to subsystem level has been performed. 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 the REL previous estimation, which was focusing Scimitar Engine and vehicle airframe items only. Table 4 reports the results for RDTE cost estimation while Table 5 summarizes the Production costs for both the first theoretical unit produced as well as for the 200th unit, showing the impact of the learning factor. The results reported are evaluated in € 2016 and also in € 2006 to be in line 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.

Cost Item (LACPAT A2)	REL Model M€ 2006	PoliTo Model M€ 2006	PoliTo Model M€ 2017
Scimitar	8,147	5,927	8,286
Airframe	14,454	11,837	16,550
Vehicle	**22,601**	**17,764**	**24,836**

Table 4 RDTE cost estimation for LAPCAT A2

Cost Item (LAPCAT A2)	REL Model M€ 2006	PoliTo Model M€ 2006	PoliTo Model M€ 2017
Scimitar	81	77	108
Airframe	712	643	900
Vehicle	**979**	**951**	**1,332**

Table 5 Production cost estimation for LAPCAT A2 TFU

Cost Item (LAPCAT A2)	REL Model M€ 2006	PoliTo Model M€ 2006	PoliTo Model M€ 2017
Scimitar	22	26	37
Airframe	265	122	170
Vehicle	**353**	**226**	**318**

Table 6 Production cost estimation for LAPCAT A2 200th unit produced

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 4). 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 PBS and WBS is reported in pie-charts of Fig. 11 and Fig. 12. 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.

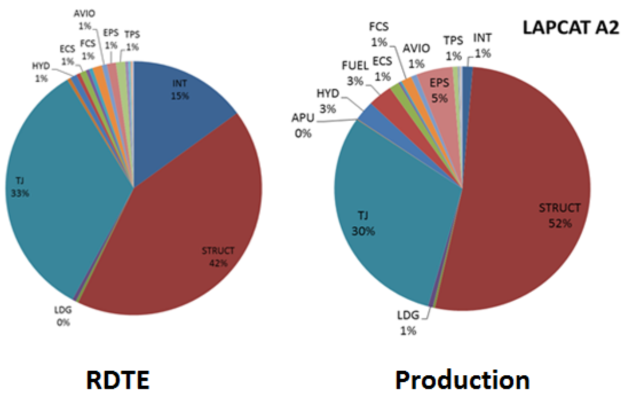

Fig. 11 PBS costs allocation for LAPCAT A2

Other on-board subsystems complete the breakdown (Fig. 11 shows those which have an impact on cost greater than 1%). Looking at WBS 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).

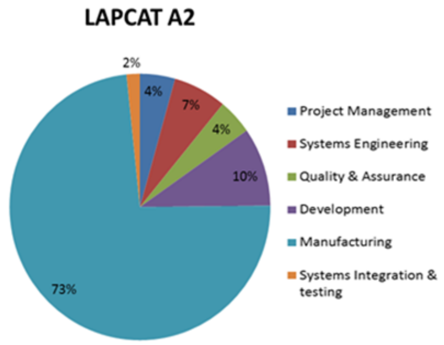

Fig. 12 WBS costs allocation for LAPCAT A2

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.
Considering DOC, the results are reported for both the EU and the US scenarios referred to the LH2 production the terms of cost per flight for the year 2017 (see Table 7). It is specified that a fuel cost of 3.15 \$/kg has been assumed for the US productive scenario, whilst 4.27 \$/kg for the EU scenario. 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 [11] and ICAO [12].(see Table 8). It is specified that IOC results are valid for both the A2 and the MR2 configurations.

Cost Item	Cost, [€2017/flight], EU scenario	Cost, [€2017/flight], US scenario
DOC_F	818,339	604,859
DOC_C	7,711	7,711
DOC_I	9,626	9,626
DOC_D	59,647	59,647
$DOC_{M/AF/L}$	3,468	3,468
$DOC_{M/AF/M}$	6,273	6,273
$DOC_{M/CC/L}$	21,203	21,203
$DOC_{M/CC/M}$	21,727	21,727
DOC_M	52,671	52,671
Total DOC	947,994	734,514

Table 7 DOC Results for A2 vehicle

IOC Item	Value, [€2017/Flight]
Station and Ground	52,088
Traffic Service	3,185
Passenger Service	39,578
Reservation and Sales	43,029
General and Administrative	40,764
Aircraft Servicing	755
Airport Charges and Air Navigation Charges	46,992
Total	226,931

Table 8 IOC Results for both A2 and MR2 vehicles

Eventually, Fig. 13 shows the TOC breakdown for the A2 vehicle derived from Table 7 and Table 8 and valid for the EU LH2 production scenario.

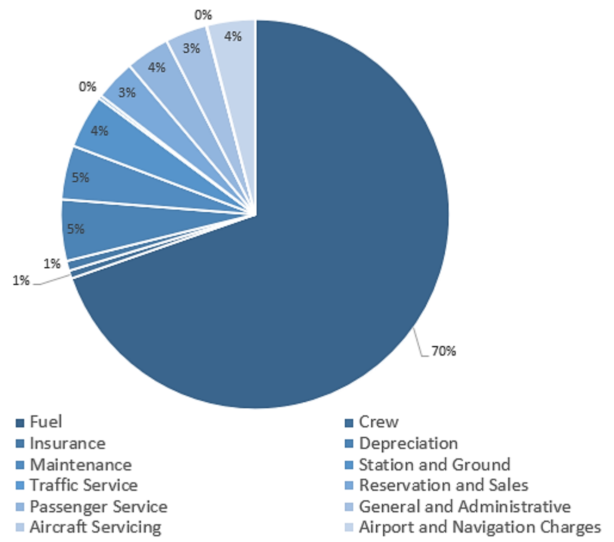

Fig. 13 TOC cost breakdown for A2 cruiser

4.2 LAPCAT MR2 LCC estimation

The estimations derived for LAPCAT MR2 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.

Cost Item (LAPCAT MR2)	PoliTo Model M€ 2017
ATR	5,635
DMR	1,708
Airframe	17,639
Vehicle	**24,982**

Table 9 RDTE cost estimation for LAPCAT MR2

Cost Item (LAPCAT MR2)	PoliTo Model M€ 2017
ATR	71
DMR	35
Airframe	940
Vehicle	**1,401**

Table 10 Production cost estimation for LAPCAT MR2 TFU

Cost Item (LAPCAT MR2)	PoliTo Model M€ 2017
ATR	23
DMR	13
Airframe	189
Vehicle	**340**

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

The overall RDTE cost for MR2 is higher if compared to A2, even if the powerplant development is cheaper (Scimitar engine is way more complex than ATR/DMR). The increase of RDTE airframe cost is instead mainly due to the higher cruise speed (which has impact on configuration also). This is also evident on production cost, even if in this case the contribution of the overall powerplant becomes important (the number of engines installed is higher than in the case of A2).

The contributions of PBS and WBS items are shown in Fig. 14 and Fig. 15. As for the A2, the main RDTE items are structure and powerplant (both ATR and DMR).

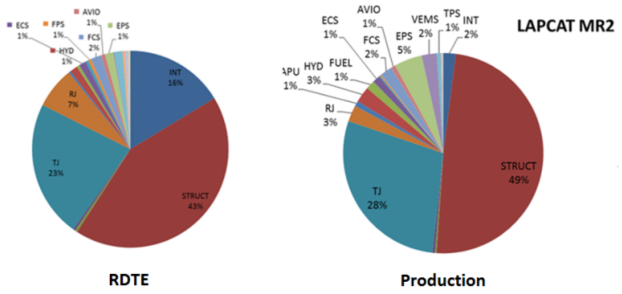

Fig. 14 PBS costs allocation for LAPCAT MR2

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.

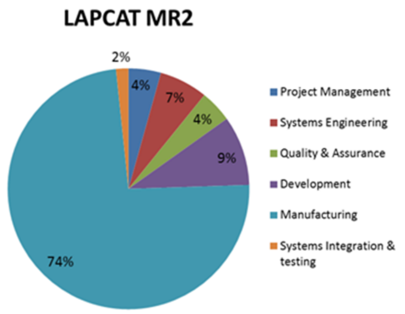

Fig. 15 WBS costs allocation for LAPCAT MR2

WBS items are also in line with A2 estimations following this preliminary computation.
Table 12 summarizes the results concerning DOC estimation for LAPCAT MR2.

Cost Item	Cost, [€2017/flight], EU scenario	Cost, [€2017/flight], US scenario
DOC_F	818,339	604,859
DOC_C	4,849	4,849
DOC_I	10,433	10,433
DOC_D	64,088	64,088
$DOC_{M/AF/L}$	2,856	2,856
$DOC_{M/AF/M}$	4,488	4,488
$DOC_{M/TJ/L}$	1,227	1,227
$DOC_{M/TJ/M}$	10,191	10,191
$DOC_{M/RJ/L}$	1,091	1,091
$DOC_{M/RJ/M}$	2,044	2,044
DOC_M	21,897	21,897
Total DOC	919,606	706,126

Table 12 DOC Results for MR2 vehicle

4. Conclusions and Future Works

The research activity carried out by Politecnico di Torino in collaboration with the European Space Agency, allows to derive a new formulation for the Life Cycle Cost estimation of innovative hypersonic transportation systems. The suggested methodology as well as the mathematical algorithms have been validated using LAPCAT A2 project as reference. Moreover, additional results have been provided for the LAPCAT MR2 vehicle configuration.
Politecnico di Torino is currently working on the implementation of all the developed algorithms into an automatic tool called HyCost. Eventually, further development of the methodology and of the tool will be focused on the assessment of the impact of technological improvements into costs.

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