Life-Cycle Cost Estimation for High-Speed Vehicles: from the engineers’ to the airline’s perspective

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Abstract

This paper aims at upgrading the holistic Cost Estimation methodology for High-Speed Vehicles already developed by Politecnico di Torino and the European Space Agency (ESA) to encompass different stakeholders' perspectives. In details, the presented methodology combines International Air Transport Association (IATA) best practices with a detailed Life-Cycle Cost (LCC) assessment, which includes the evaluation of Research, Development, Test and Evaluation (RDTE) Costs, Production costs and of Direct and Indirect Operating Costs (DOC and IOC). The integrated approach allows to further extend the capabilities of the in-house developed HyCost tool to support all the actors of the product value-chain (including engineers, manufacturers, airlines and customers) in assessing the economic sustainability of a newly under-development high-speed vehicle. However, considering the need of providing all these cost analyses perspectives since the early design stages, the derived Cost Estimation Relationships are mainly derived on statistical bases. To cope with the uncertainties that affect the initial statistical population and consequently, the CERs, this paper presents each cost item together with the estimation of related prediction intervals. Finally, results of the application of the upgraded cost estimation methodology and of the upgraded tool to the LAPCAT MR2.4 high-speed civil transport are reported and discussed.

1. Introduction

The economic feasibility and sustainability of future high-speed vehicles and mission concepts is currently considered as one of the major challenges for engineers, involved in the design, development, test and production phases, as well as for airlines that are willing to operate these new vehicles. Moreover, the success of these new products on the market will highly depend on the final ticket price that might reduce the attractiveness of high-speed flight. Furthermore, considering that, as mentioned by Roskam [1], the costs sustained by an airline to operate an aircraft through the years constitute the greatest part of the costs incurred during the overall product life cycle, Politecnico di Torino and the European Space Agency (ESA) have introduced some upgrades to the innovative integrated Life-Cycle Cost (LCC) Estimation Methodology [2] [3] to support engineers, manufacturers, airlines and generic customers to perform a rapid economic assessment of future high-speed vehicles and mission concepts. However, it is worth noticing that one of the major challenges to be faced in this context is related to the need of providing all these standpoints on cost estimation very early during the design activity, when the main design variables may be affected by relevant levels of uncertainties, usually expressed as design margins. Of course, these margins become uncertainties onto the main cost drivers and depending on the mathematical formulation of the Cost Estimation Relationship (CER) they might have a different impact onto the final cost items. Conversely, it is more complicated to capture the uncertainties that affect the different semi-empirical coefficients of the CERs because they are strictly related to the initial statistical population from which they have been derived. In this context, this paper provides an updated version of the Cost Estimation Methodology proposed by the same authors in [2] and [3] to properly capture the effect of the initial statistical population on to the various cost items and eventually onto the different cost estimation perspectives.

In details, after this brief introduction, Section II describes the integrated cost assessment methodology for high-speed vehicles developed at Politecnico di Torino through the support of ESA, underlying the most recent updates. Specifically, this section highlights the possibility of considering, since the conceptual design stage, all the actors along the value-chain, from the designers and manufacturers up to airlines and passengers, providing them with dedicated cost items estimation. However, the need to carry out cost estimation as soon as possible during the design process can highly affect the accuracy of the results. Thus, Section III and Section IV of this paper describe in detail the way in which multiple standpoints can be implemented since the early conceptual design. Respectively, Section III reports the analysis and estimation of the Prediction Intervals for the main Research, Development, Test and Evaluation (RDTE) and Production cost items due to the dispersion of the initial statistical population used to derive the coefficients of the CERs. When possible, prediction intervals for both confidence intervals of 95% and 99% are evaluated and discussed. Complementary, Section IV specifically focuses on the possibility of offering different cost estimation perspectives, allowing for the LCC estimation as well as for the ticket price calculation for future high-speed travels. In particular, benefitting from the analysis carried out in Section III, error margins are also included in the Cost Estimations in the different standpoints. In addition, for the sake of clarity, Section IV also presents the application of prediction boundaries estimation and their effect up to the ticket price for the LAPCAT MR2.4 reference high-speed vehicle [4], [5]. Results are discussed, providing a comparison with respect to currently long-haul aircraft costs and ticket prices. At the end, main conclusions are drawn and ideas for future upgrades of the methodology and tool as well as for their application to a wider spectrum of case studies are presented.

2. Cost Estimation Methodology and tool: background and upgrades

The renewed interest of aviation to design and develop very high-speed aircraft urges all the actors of the value-chain to verify the economic sustainability of the new under-development products. In this context, the integrated and flexible methodology already published in [2] and [3] and implemented within the HyCost tool is a valuable starting point to extend the evaluation of cost estimation to cover a wider spectrum of stakeholders and standpoints as well as to enrich the cost items estimation with proper prediction boundaries. Fig. 1 briefly describes the methodology developed by Politecnico di Torino with the ESA support that is currently implemented within the HyCost tool.

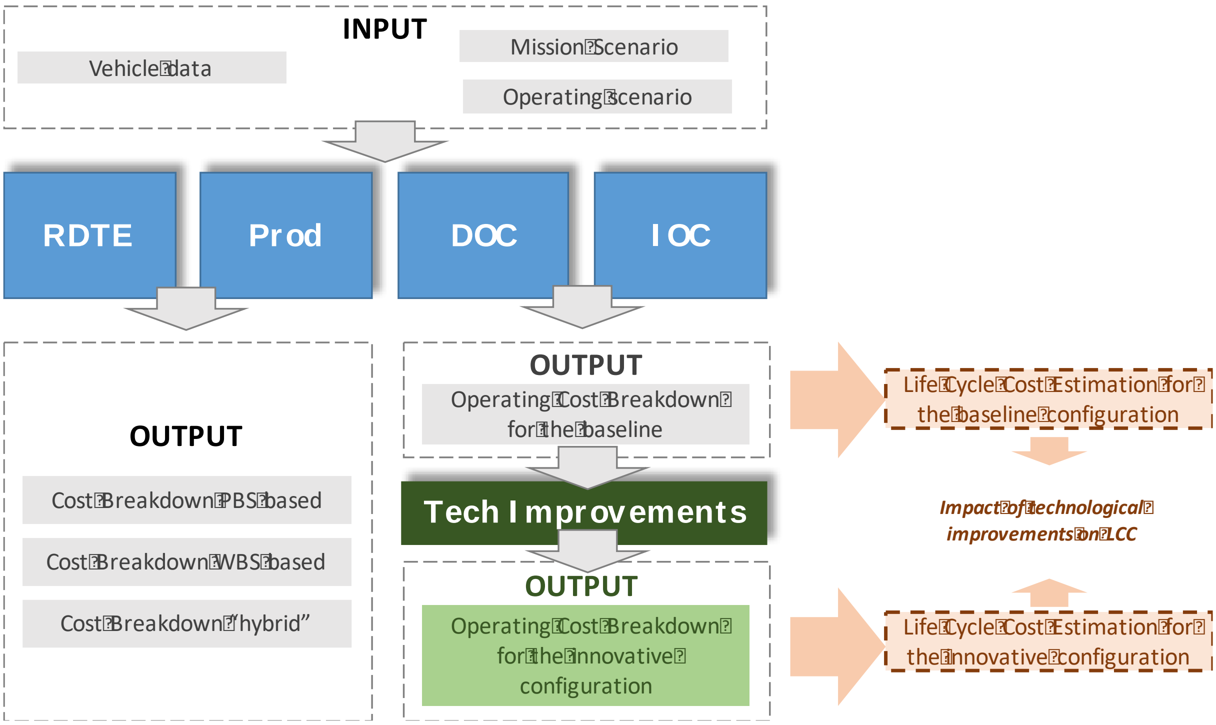

Fig. 1 Cost Estimation Methodology implemented in HyCost Tool

In short, as far as the engineers' perspective is concerned, an in-depth literature review has been carried out and the results confirmed the existence of cost estimation models that could be applied to high-speed studies only partially. In particular, TransCost model [6] has been taken into account especially as a base for the derivation of the RDTE and Production CERs. As far as Direct Operating Cost (DOC) is considered, in the past, different approaches have been presented by the Air Transport Association of America (ATA) [7], Association of European Airlines (AEA) [8], and Liebeck [9] to assess LCC of civil subsonic aircraft, but they appear to be specifically tailored to their reference vehicle architecture. A more generic approach specifically referred to high-speed vehicles was suggested by National Aeronautics and Space Administration (NASA) in 1973 [10]. In particular, [10] has been 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 method [7]. The complete set of CERs encompassing RDTE, Production, DOC and Indirect Operating Cost (IOC) cost items has been presented in [2]. In addition, considering that DOC represents a very high percentage of entire LCC for high-speed vehicles and considering that the most impacting driver is represented by fuel cost, the HyCost methodology has been recently upgraded with a specific cost estimation routine able to provide more accurate fuel cost [3]. Moreover, it is worth mentioning that works are on-going to improve the technology improvement routine that allows the user to assess the impact of a technological improvement on to the various cost items and eventually on the entire LCC.
In this already well-defined context, the authors have decided to widen the scope of the HyCost methodology to support not only designers and engineers, but also manufacturers, airlines and customers to verify the economic sustainability of these new high-speed products since their initial stage of development.

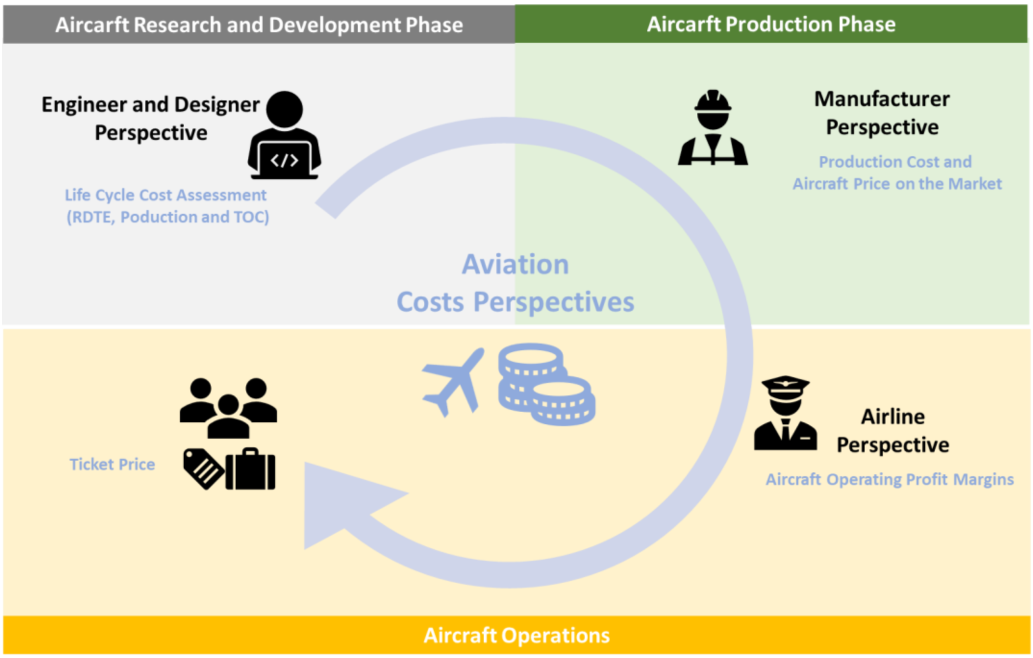

Fig. 2 Summary of Aviation Costs Perspectives

Looking at Fig. 2, for the Engineers and Designers Perspectives, as well as for the Manufacturers perspective, HyCost is already able to support the estimation of RDTE and Production Costs. The estimation of Operating cost is important but not sufficient to prove the economic sustainability of the product for an airline. Similarly, the estimation of the overall LCC might be not very meaningful for a generic customer who might be simply interested into the final ticket price. To ensure that all stakeholders have the elements to assess the economic sustainability of the flight, the four different perspectives reported in Fig. 2 have been in-depth investigated and they are formalized in Section IV. To support this activity, a specific literature review has also been completed and some documents have been identified as useful basis for the integration of this multiple standpoints approach. In particular, the NASA model presented in [11] has been carefully revised and considered as a valuable starting point for the estimation of both the airline and travelers' perspectives. In addition, International Air Transport Association (IATA) guidelines can be followed to define and estimate proper profit margins [12].

However, it is important to notice that all these cost estimations shall be carried out at the very beginning of the design process and this implies a consistent exploitation of statistically derived CERs. In line with what it is usually carried out in design activities, where design margins are used to support the preliminary design variables estimation, this paper aims at suggesting an integrated approach to support the cost estimation with proper prediction boundaries. These margins shall be able to reflect the uncertainties in the semi-empirical coefficients of the regression curves, which have originated the core functions of the CERs and which can be highly affected by the limited amount of available statistical population.

3. Estimation of Prediction Intervals on Cost Estimation Relationships

According to [6], a generic CER equation can be expressed as a function of a certain number of design variables, usually referred to as cost drivers and a set of semi-empirical coefficients. Looking at Fig. 3 it is possible to see that the uncertainties onto the cost items can mainly be due to (i) uncertainties onto the cost drivers and (ii) uncertainties onto the cost parameters. As far as the uncertainties on cost drivers estimation, they can be easily computed on the basis of the design margins that affect the estimation of each cost driver, that usually represent important design variables. Conversely, it is not so easy the evaluation of the uncertainties due to the cost parameters variation. Indeed, each cost parameter, at conceptual design stage, basically represents a semi-empirical coefficient derived from a statistical analysis. Considering that the statistical population related to high-speed vehicles is very limited and sometimes it might already be affected by some uncertainties, the resulting semi-empirical formulation shall be described not only by looking at the nominal trend but also at its neighborhood, i.e. defining proper prediction intervals. Specifically, this Section of the paper aims at describing the results of the estimation of prediction intervals on RDTE and PROD cost items and their impact onto DOC.

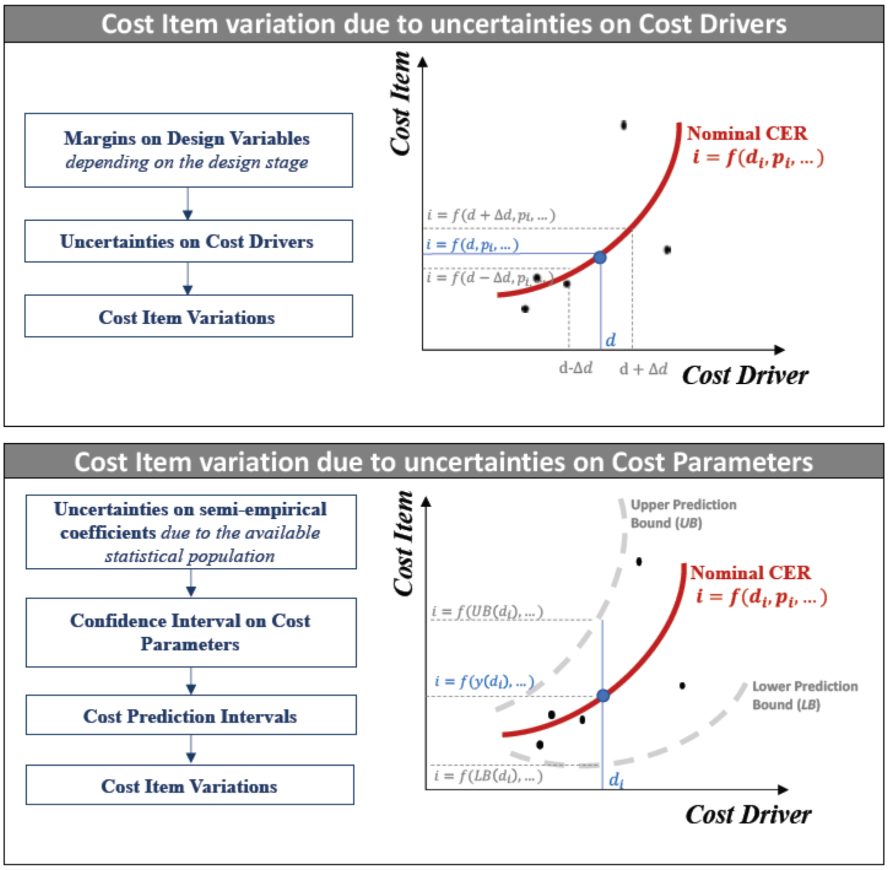

Fig. 1 Cost Items variations due to uncertainties on Cost Drivers and on Cost Parameters

Confidence and prediction bounds define the lower and upper values of an associated interval, and define the width of the interval itself. The width of the interval indicates the uncertainty that affects the fitted coefficients, the predicted observation, or the predicted fit. For example, a very wide interval for the fitted coefficients (i.e. a very wide confidence bound) can indicate that more data shall be used when fitting to properly definite the set of semi-empirical coefficients. The bounds are defined with a level of certainty which is often set to a 95% value, even if other Confidence Intervals can be considered. For the sake of clarity, if the user wants to take a 5% chance of being incorrect about the predicted cost item, a prediction interval evaluated on a 95% confidence interval shall be considered. The evaluated prediction interval indicates that the user has a 95% chance that the cost item estimation is actually contained within the lower and upper prediction bounds. According to statistical modelling techniques, the prediction intervals can be generically expressed with the following equation:

$$Prediction\ Bounds = y \pm t\sqrt{s^2 + xSx^T} \tag{1}$$

Where:

s^2 is the mean squared error;

t depends on the confidence interval, and is computed using the inverse of Student's t cumulative distribution function;

S is the covariance matrix of the coefficient estimates, $(X^T X)^{-1} s^2$.

X : in a linear fit, it is the design matrix, while for a nonlinear fit X is the Jacobian of the fitted values with respect to the coefficients

x is a row vector of the design matrix or Jacobian evaluated at a specified predictor value.

Considering all the CERs formulation reported in [2], it is evident that the highest impact of uncertainties of the statistical population is expected onto RDTE and PROD main cost items. Subsequently, considering that many Direct Operating Cost items depend upon the vehicle or the engines acquisition costs, the impact of uncertainties can be indirectly estimated for TOC as well.

Please notice that the analysis is performed only looking at the so called "core" CER, i.e. without taking into account multiplying factors that are usually inserted to steer the cost estimation on the basis of engineering judgement and experience. The CERs provided in the following subsection are built on statistical population whose cost values have been translated into M€ 2019.

The statistical database that has been used in the following analysis consists of the original dataset presented in [6] improved to include the newest concepts of high-speed transportation as described in [2].

1. Prediction Intervals estimation on Airframe RDTE Cost

Fig. 4 reports the results of the statistical analysis at the basis of the derivation of the Cost Estimation Relationship describing the cost associated to the research and development activities for a high-speed airframe. Mathematical formulation of the nominal CER as well as of the lower and upper prediction interval bounds for both 95% and 99% of confidence intervals are reported in Table I. In addition, the numerical results for the LAPCAT MR2.4 vehicle configuration are reported in Table II.

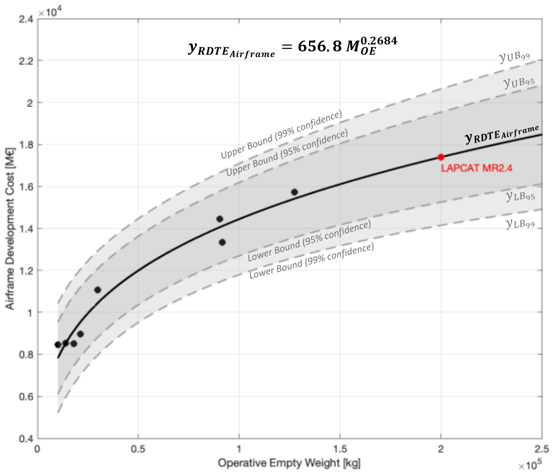

Fig. 2: RDTE Airframe CER and Prediction Bounds

Table I: RDTE Cost of Airframe: mathematical model of CER and Prediction Bounds

Nominal CER: $y_{RDTE_{Airframe}} = 656.8\ M_{OE}^{0.2684}$ (2)		
Confidence intervals	**Lower Bound Equation**	**Upper Bound Equation**
95%	$y_{LB_{95}} = 477.9\ \mathrm{x}^{0.28}$ (3)	$y_{UB_{95}} = 853.9\mathrm{x}^{0.26}$ (4)
99%	$y_{LB_{99}} = 394.1\ \mathrm{x}^{0.29}$ (5)	$y_{UB_{99}} = 961.5\ \mathrm{x}^{0.25}$ (6)

Table II: RDTE Cost of Airframe: LAPCAT MR2.4 estimation

RDTE Cost Estimation for Airframe of LAPCAT MR2.4			
Confidence intervals	**Best Case Scenario [$M€_{2019}$]**	**Nominal Scenario [$M€_{2019}$]**	**Worst Case Scenario [$M€_{2019}$]**
95%	15,300 (-%)	17,395	19,489 (+%)
99%	14,219	17,395	20,568

2. Prediction Intervals estimation on Turbojet RDTE Cost

Fig. 5 reports the results of the statistical analysis at the basis of the derivation of the CER describing the cost associated to the research and development activities for a generic Turbojet-like engine for high-speed vehicles. Mathematical formulation of the nominal CER as well as of the lower and upper prediction interval bounds for both 95% and 99% of confidence interval are reported in Table III In addition, the numerical results for the LAPCAT MR2.4 vehicle configuration are reported in Table IV.

$$y_{RDTE_{TJ}} = 68.93\, M_{TJ_{dry}}^{0.5192} + 0.8594\, v$$

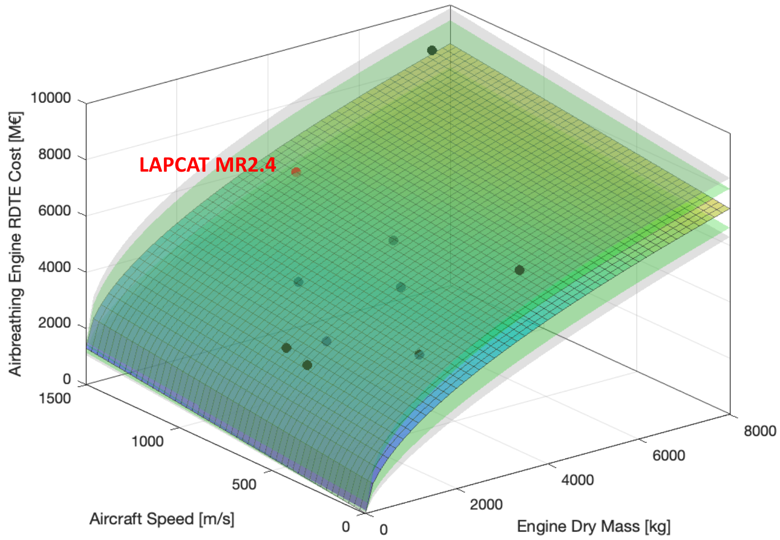

Fig. 5 RDTE Turbojet CER and Prediction Bounds

Table III: RDTE Cost of Turbojet: mathematical model of CER and Prediction Bounds

Nominal CER: $y_{RDTE_{TJ}} = 68.93\, M_{TJ_{dry}}^{0.52} + 0.86\, v.$ (7)		
Confidence interval	**Lower Bound Equation**	**Upper Bound Equation**
95%	$y_{LB_{95}} = 29.42\, M_{tj_{dry}}^{0.60} + 0.76\, v$ (8)	$y_{UB_{95}} = 132.4\, M_{tj_{dry}}^{0.46} + 0.94\, v$ (9)
99%	$y_{LB_{99}} = 17.04\, M_{tj_{dry}}^{0.66} + 0.70\, v$ (10)	$y_{UB_{99}} = 175.2\, M_{tj_{dry}}^{0.43} + 0.97$ (11)

Table IV: RDTE Cost of Turbojet: LAPCAT MR2.4 estimation

RDTE Cost Estimation for Turbojet (ATR) of LAPCAT MR2.4			
Confidence interval	**Best Case Scenario [$M€_{2019}$]**	**Nominal Scenario [$M€_{2019}$]**	**Worst Case Scenario [$M€_{2019}$]**
95%	5402 (-%)	6271	7120
99%	4943	6271	7552

3. Prediction Intervals estimation on Ramjet/Scramjet RDTE Cost

Fig. 6 reports the results of the statistical analysis at the basis of the derivation of the CER describing the cost associated to the research and development activities for a generic Ramjet/Scramjet engine for high-speed vehicles. In this case, the very limited dataset prevents from the evaluation of prediction interval bounds. However, in this case the prediction for LAPCAT MR2.4 reference vehicle is about 1023 M€.

$$y_{RDTE_{Ramjet}} = 65.74\, M_{RJ_{dry}}^{0.3789}$$

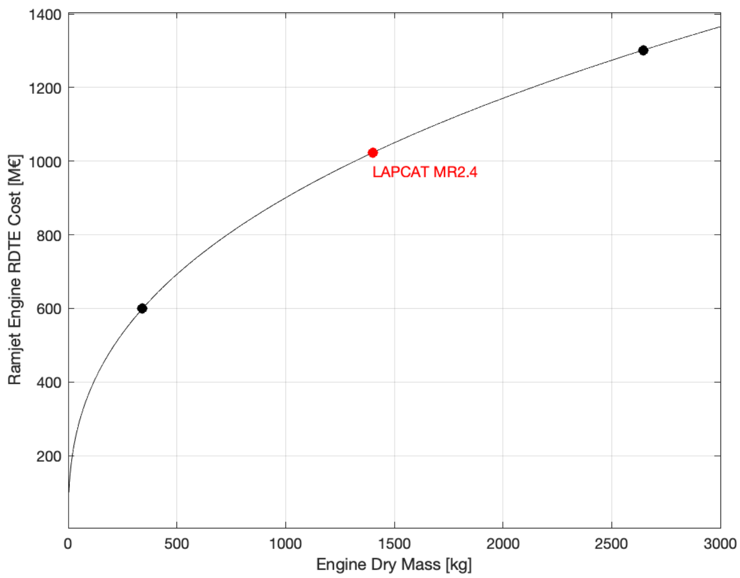

Fig. 6 RDTE Ramjet CER

4. *Prediction Intervals on Total RDTE Cost estimation for LAPCAT MR2.4*

Table V summarizes the results of the uncertainty analysis on RDTE cost estimation for LAPCAT MR2,4 vehicle configuration.

Table V: Total RDTE Cost Estimation for LAPCAT MR2.4

RDTE Cost Estimation for LAPCAT MR2.4			
Cost Item	**Best Case Scenario** *Lower Prediction Bound with 99% CI [$M€_{2019}$]*	**Nominal Scenario [$M€_{2019}$]**	**Worst Case Scenario** *Upper Prediction Bound with 99% CI [$M€_{2019}$]*
ATR	4943	6271	7552
DMR	806*	1023	1232*
Airframe	14,219	17,395	20,568
TOTAL RDTE	19,968 (-19%)	24,689	29,352 (+19%)
*The DMR lower and upper boundaries have assumed similar to those derived from the Turbojet analysis			

5. *Prediction Intervals estimation on Airframe PROD Cost*

Fig. 7 reports the results of the statistical analysis at the basis of the derivation of the Cost Estimation Relationship describing the cost associated to the production of the Airframe Theoretical First Unit (TFU) for a high-speed vehicle. Mathematical formulation of the nominal CER as well as of the lower and upper prediction interval bounds for both 95% and 99% of confidence interval are reported in Table VI. In addition, the numerical results for the LAPCAT MR2.4 vehicle configuration are reported in Table VII This Table reports also the estimation for the 200th Theoretical Unit, assuming that for the Airframe Production, a the learning curve factor of 83%.

$$y_{PROD\_Airframe} = 5.06 \cdot 10^{-7}\, M_{OE}^{1.768} + 7.06\, v^{0.332}$$

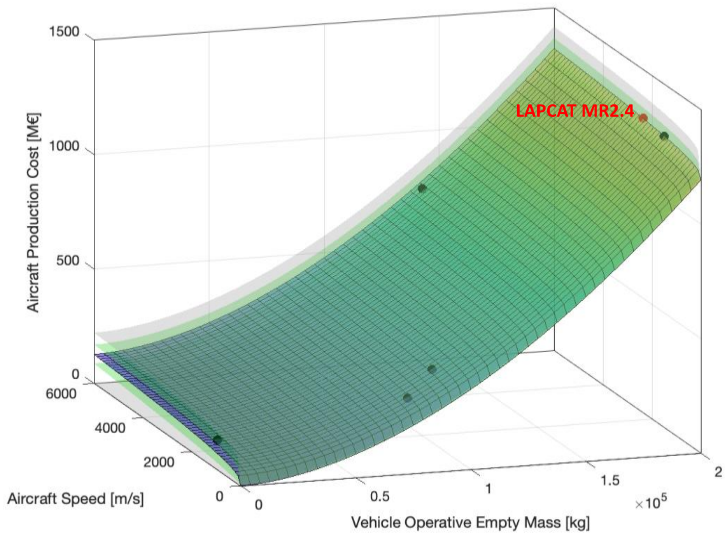

Fig. 7 PROD Airframe CER and Prediction Bounds

Table VI: PROD Cost of Airframe: mathematical model of CER and Prediction Bounds

Nominal CER: $y_{PROD\_Airframe} = 5.06 \cdot 10^{-7}\, M_{OE}^{1.77} + 7.06\, v^{0.33}$ **(12)**		
Confidence Interval	**Lower Bound Equation**	**Upper Bound Equation**
95%	$y_{LB_{95}} = 5.29\ 10^{-7}\ M_{OE}^{1.76} + 0.397\ v^{0.62}$ (13)	$y_{UB_{95}} = 5.60\ 10^{-7}\ M_{OE}^{1.76} + 24.02\ v^{0.22}$ (14)
99%	$y_{LB_{99}} = 5.41\ 10^{-7}\ M_{OE}^{1.76} + 0.273 v^{0.65}$ (15)	$y_{UB_{99}} = 3.06\ 10^{-6} M_{tj_{dry}}^{1.62} + 32.35 v^{0.18}$ (16)

Table VII: PROD Cost of Airframe: LAPCAT MR2.4 estimation

PROD Cost Estimation for Airframe of LAPCAT MR2.4				
	Confidence Interval	**Best Case Scenario [$M€_{2019}$]**	**Nominal Scenario [$M€_{2019}$]**	**Worst Case Scenario [$M€_{2019}$]**
TFU	**95%**	1262	1287	1289
	99%	1240	1287	1308
200th unit	**95%**	303.74	309.76	310.24
	99%	298.45	309.76	314.81

6. Prediction Intervals estimation on Turbojet PROD Cost

Fig. 8 reports the results of the statistical analysis at the basis of the derivation of the Cost Estimation Relationship describing the cost associated to the production of the Turbojet First Theoretical First Unit (TFU) for a high-speed vehicle. Mathematical formulation of the nominal CER as well as of the lower and upper prediction interval bounds for both 95% and 99% of confidence interval are reported in Table VIII. In addition, the numerical results for the ATR TFU for the LAPCAT MR2.4 vehicle configuration are reported in Table IX This Table reports also the estimation for the 200th Vehicle Theoretical Unit (an average of the 1195th and 1200th ATR) assuming that for the Turbojet Engine Production, a factor of the learning curve of 88%.

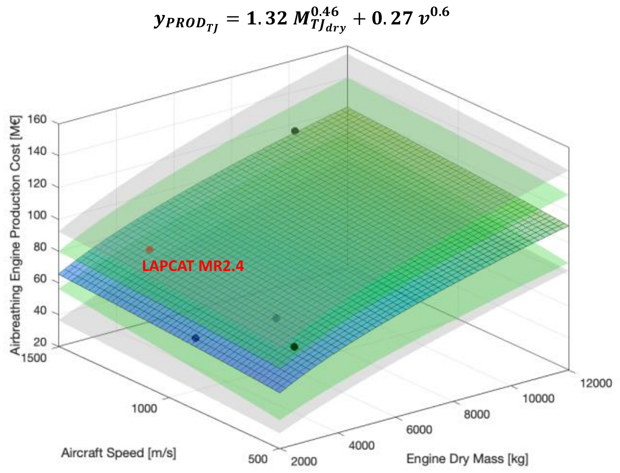

Fig. 8 PROD Turbojet CER and Prediction Bounds

Table VIII: PROD Cost of Turbojet: mathematical model of CER and Prediction Bounds

Nominal CER: $y_{PROD_{TJ}} = 1.32\ M_{TJ_{dry}}^{0.46} + 0.27\ v^{0.6}$ **(17)**		
Confidence Interval	**Lower Bound Equation**	**Upper Bound Equation**
95%	$y_{LB_{95}} = 0.78\ M_{TJ_{dry}}^{0.51} + 0.069\ v^{0.67}$ (18)	$y_{UB_{95}} = 0.68\ M_{TJ_{dry}}^{0.53} + 7.46\ v^{0.23}$ (19)
99%	$y_{LB_{99}} = 0.20\ M_{TJ_{dry}}^{0.64} + 0.022\ v^{0.85}$ (20)	$y_{UB_{99}} = 0.58\ M_{TJ_{dry}}^{0.55} + 15.69\ v^{0.17}$ (21)

Table IX: PROD Cost of Turbojet: LAPCAT MR2.4 estimation

PROD Cost Estimation for LAPCAT MR2.4 ATR engine				
	Confidence Interval	**Best Case Scenario [$M€_{2019}$]**	**Nominal Scenario [$M€_{2019}$]**	**Worst Case Scenario [$M€_{2019}$]**
TFU	**95%**	66.79	80.45	95.45
	99%	49.25	80.45	108.52
200th vehicle	**95%**	18.07	21.76	25.83
	99%	13.33	21.76	29.36

7. Prediction Intervals estimation on Ramjet/Scramjet PROD Cost

Fig. 9 reports the results of the statistical analysis at the basis of the derivation of the Cost Estimation Relationship describing the cost associated to the production of the Ramjet/Scramjet Theoretical First Unit (TFU) for a high-speed vehicle. Mathematical formulation of the nominal CER as well as of the lower and upper prediction interval bounds for the 95% and 99% confidence interval are not reported considering that they present a significant difference with respect to the other cases and this is mainly due to the very meager dataset. However, in this case the prediction for DMR of the LAPCAT MR2.4 reference vehicle is about 21.48 M€.

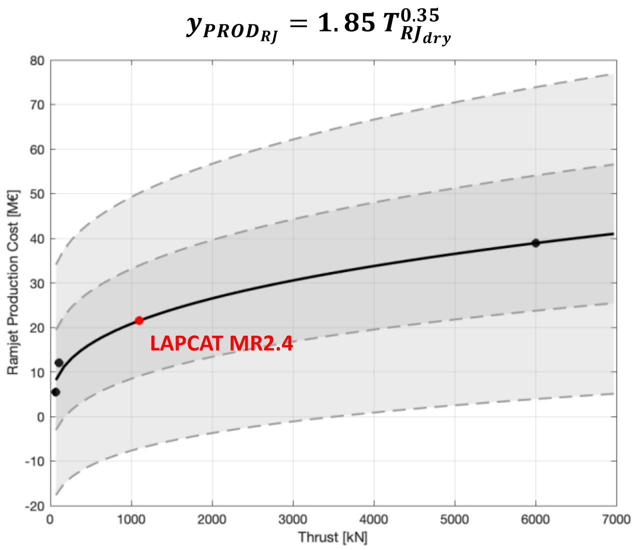

Fig. 9 PROD Ramjet CER and Prediction Bounds

8. Prediction Intervals on Total PROD Cost estimation for LAPCAT MR2.4

Table X and Table XI summarize the results of the Production Cost Estimation for LAPCAT MR2.4 vehicle configuration. In details, Table X reports the Production Cost for the Theoretical First Unit while Table XI reports the estimation for the 200th vehicle unit.

Table X: TFU PROD Cost summary for LAPCAT MR2.4

PROD Cost Estimation for LAPCAT MR2.4 (Vehicle TFU)			
Cost Item	**Best Case Scenario** *Lower Prediction Bound with 99% CI* $[M€_{2019}]$	**Nominal Scenario** $[M€_{2019}]$	**Worst Case Scenario** *Upper Prediction Bound with 99% CI* $[M€_{2019}]$
ATR	49.25 (37.76**)	80.45 (66.07**)	108.52 (92.16**)
DMR	21.48	13.57*	29.38*
Airframe	1287	1240	1308
TOTAL PROD TFU	**1535 (-7%)**	**1650**	**1890 (+14.5%)**
*The DMR lower and upper boundaries have assumed similar to those derived from the Turbojet analysis **In brackets the average value of one of the 6 ATR to be integrated onto the first vehicle unit			

Table XI: 200th Vehicle Unit PROD Cost summary for LAPCAT MR2.4

PROD Cost Estimation for LAPCAT MR2.4 ATR engine				
	Confidence Interval	**Best Case Scenario** $[M€_{2019}]$	**Nominal Scenario** $[M€_{2019}]$	**Worst Case Scenario** $[M€_{2019}]$
TFU	**95%**	66.79	80.45	95.45
	99%	49.25	80.45	108.52
200th vehicle	**95%**	18.07	21.76	25.83
	99%	13.33	21.76	29.36

9. Prediction Intervals on Total Operating Cost estimation for LAPCAT MR2.4

The prediction intervals derived for the main RDTE and Production costs are indirectly imposing upper and lower boundaries also to some of the DOC. This is due to the relationships that acquisition costs have onto some of the DOC items, such as Insurance, Depreciation and Maintenance. Conversely, variations onto other items such as Fuel Cost, Crew Cost and Maintenance Labor Costs are not here evaluated considering that they are not affected by the variation of acquisition costs. Details of the estimation of boundaries for the LAPCAT MR2.4 vehicle are hereafter reported.

Table XII: Total Operating Cost summary for LAPCAT MR2.4

Total Operating Costs Estimation				
Cost Item	**Definition**	**Best Case Scenario** *Lower Prediction Bound with 99% CI [$€_{2019}$/flight]*	**Nominal Scenario [$€_{2019}$/ $flight$]**	**Worst Case Scenario** *Upper Prediction Bound with 99% CI [$€_{2019}$/ $flight$]*
DOC_{Fuel}	**Fuel Cost**	360,000	360,000	360,000
DOC_{Crew}	**Crew Cost**	4946	4946	4946
$DOC_{Insurance}$	**Insurance Cost**	11,675	13,651	15,283
$DOC_{Depreciation}$	**Depreciation Cost**	68,094	81,416	92,607
$DOC_{M/AF/L}$	**Maintenance Cost (Airframe Labour)**	2913	2913	2913
$DOC_{M/AF/M}$	**Maintenance Cost (Airframe Material)**	4465	4634	4710
$DOC_{M/ATR/L}$	**Maintenance Cost (ATR Engine Labour)**	1252	1252	1252
$DOC_{M/ATR/M}$	**Maintenance Cost (ATR Engine Material)**	5798	9471	12,776
$DOC_{M/DMR/L}$	**Maintenance Cost (DMR Engine Labour)**	1113	1113	1113
$DOC_{M/DMR/M}$	**Maintenance Cost (DMR Engine Material)**	833	1318	1803
Total DOC	**Total Direct Operating Cost**	**461,089 (-4%)**	**480,715**	**497,402 (+3.5%)**
Total IOC	**Total Indirect Operating Costs**		**226,931**	
TOC	**Total Operating Costs**	**688,020**	**707,646**	**724,333**

4. From LCC estimation to Ticket Price formulation: implementation of different perspectives onto cost estimation

Once the Cost Estimation Relationships for RDTE, PROD and TOC have been fully addressed and upgraded with the indication of the related prediction boundaries, it is possible to look at the problem from different perspectives. Looking at the high-speed vehicle product throughout the value-chain, four different main perspectives onto cost estimation can be of interest.

The starting point is of course the Researcher and Engineer standpoint that looks at the sustainability of the under-development product looking at the entire Life Cycle. For this reason, the current HyCost version perfectly fits the need of this stakeholder's category.

Moving forward into the value-chain, it is important to verify the economic sustainability of the product from the Manufacturer standpoint. The current version of HyCost can only partially fulfill the requirements of this stakeholders because it is able to provide Production Cost Estimations and a cost breakdown up to subsystem level, but HyCost does not provide any suggestions for the definition of proper profit margins to be defined onto the acquisition costs as well as on the amount of development cost to be allocated onto each item. It is worth noticing that in the case of high-speed transportation, manufacturers are only partially involved into the research and development activities so that these costs can be neglected for the actual aircraft selling price. Therefore, to properly address the manufacturer perspective, it is important to define proper profit margins that according to the general best practices of aviation are about the 10% of the Production Costs.

Moving forward into the value-chain, it is then necessary to provide the Airlines that might be interested in operating this new type of aircraft with all the elements that are necessary to estimate the Aircraft Operating Cost and eventually the Net Revenues per passengers per flight. In this context, the following approach is hereafter suggested.

First of all, the Airline shall compute the expected gross revenue per flight that in order be economically sustainable shall be greater than the overall aircraft operating cost. For this reason, the equation (Eq. 22) is suggested for the Revenue evaluation.

$$\text{Revenue per flight} = TOC + Profit\ Margin \tag{2}$$

IATA guidelines (reported in Fig. 10), can be used to properly hypothesize the Profit Margin, here called EBIT (5.1% is here used as reference), i.e. the Earnings Before Interest and Tax. Thus, Eq. (22) can rewritten accordingly:

Worldwide airline Industry	2018	2019E	2020F
Industry ROIC, % invested capital	6.5%	5.7%	6.0%
North America	9.0%	9.9%	9.1%
Europe	8.8%	6.8%	7.7%
Asia-Pacific	4.3%	3.2%	4.5%
Latin America	5.0%	4.9%	5.2%
EBIT margin, % revenue	5.7%	5.1%	5.5%
Net post-tax profits, $billion	27.3	25.9	29.3
% revenues	3.4%	3.1%	3.4%
$ per passenger	6.22	5.70	6.20
Adjusted net debt/EBITDAR	4.50	4.60	4.50

Note: ROIC = Return on Invested Capital, EBIT = Earnings Before Interest and Tax. Debt adjusted for operating leases. **Current year or forward-looking industry financial assessments should not be taken as reflecting the performance of individual airlines, which can differ significantly.**

Fig. 10: IATA Guidelines for Profit Margin Assessment [12]

$$\text{Revenue per flight} = \frac{TOC}{(1 - EBIT)} \tag{3}$$

Then, the Net Profit Margin can be estimated following IATA suggestions, expressing them as a percentage of the gross revenues per flight (3.1% of the Revenue). Moreover, the Net Profit per Departing Passenger Per Flight can be easily estimated as:

$$\text{Net Profit Margin per Departing Passenger} = \frac{Net\ Profit\ Margin}{available\ seat * load\ factor} \tag{4}$$

The estimation of Profit Margins guarantees the possibility of moving towards the last element of the value-chain, i.e. looking at the economic sustainability of the product from the Travelers' standpoint. In this case the only important value to be estimated is the Ticket Price.

$$\text{Ticket Price} = \frac{\text{TOC} + \text{Profit Margin}}{\text{seats} * \text{load factor}} \quad (5)$$

Results for the estimations carried out for the LAPCAT MR2.4 case study are reported in Table #.

Table XIII: Different Cost Perspectives summary for LAPCAT MR2.4

Different Cost Perspectives			
	Best Case Scenario *Lower Prediction Bound with 99% CI [$€_{2019}$]*	**Nominal Scenario [$€_{2019}$]**	**Worst Case Scenario** *Upper Prediction Bound with 99% CI [$€_{2019}$]*
Gross Revenue Per Flight	724,995	745,360	763,259
Net Profit Margin	22,475	23,107	23,661
Net Profit Margin per departing passenger	100	102.7	105.2
Ticket Price	**3222 (-2.7%)**	**3313**	**3392 (+2.4%)**

Looking at the results it shall be noticed that Net Profit Margin per Departing Passenger is about 5.7$/flight/pax (about 5.2€/flight/pax) for classical subsonic aircraft vs 103 €/flight/pax for the case study here reported. This difference might be due to the fact that IATA presents average values for all airlines and, therefore, it takes into account all carriers types and routes. In addition, LAPCAT foresees an all business class configuration, therefore the expected ticket revenue and profit could be higher than the mean value for commercial airlines (having mixed class configuration). Eventually, the LAPCAT TOC is much higher than TOC of current civil aircraft, therefore the computed gross revenue is higher.

5. Conclusions

This paper suggests a methodology to move from Cost Estimation purely focused on supporting conceptual design activities to the assessment of the economic sustainability throughout the product value chain. To pursue this objective, it has been demonstrated the importance of enriching the current cost estimation formulations with prediction bounds representing the possible dispersion of the estimation results due to uncertainties into the semi-empirical model coefficients.

The impact of uncertainties on RDTE formulations brought to the estimation of prediction boundaries that are 20% higher in absolute value with respect to the nominal scenario. Production costs of the 200th vehicle unit present prediction boundaries lower than 15%.

Indirect effect onto DOC and IOC have also been evaluated and appears lower than 5%. Eventually, the impact onto the airline revenue and therefore onto the ticket price are expected to be lower than 5%.

An enhancement of the statistical population used as reference for the CER derivation can be beneficial especially for the breakthrough innovative technologies like the case of the propulsion plant of the case study. In view of the results reported in this paper, authors envisage the delivery of an upgraded version of the HyCost Tool showing prediction boundaries for all cost items, including those at subsystems levels. In addition, the updated HyCost version will be organized in different Tabs, each one providing all the elements to assess the economic sustainability of the product from the specific standpoint. Eventually, the authors are currently working at widening the flexibility of the tool to better support other types of high-speed vehicles such as reusable access to space and re-entry vehicles.

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