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Research, development and production costs prediction parametric model for future civil hypersonic aircraft

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ABSTRACT

Assessing the economic viability of new high-speed systems concepts since the early design phases is crucial for the success of future hypersonic vehicles including cruisers, reusable access-to-space and re-entry systems. Besides literature reports few parametric cost models for high-speed vehicles, all of them makes exclusively use of mass as parameter and none of the models moves beyond the vehicle level. This paper describes a new parametric cost estimation model which moves beyond the state-of-the-art methodologies (1) by integrating vehicle design and operational parameters (in addition to the mass) as cost drivers for the prediction of the vehicle life-cycle cost, (2) by introducing prediction margins accounting for the uncertainties on the data-driven correlations, (3) by providing a first estimate of the costs of every on-board subsystem, including combined cycle engines and multi-functional subsystems, (4) by increasing the granularity of the analysis up to technology level, thus providing a valuable support to Technology Roadmaping activities. The parametric cost estimation model has been refined and exploited in the context of the Horizon 2020 STRATOFLY project, where the technological, operational, environmental, and economic viability of a Mach 8 waverider concept have been investigated.

1. Introduction

In recent years, advances in different scientific and technological fields have cleared a path for hypersonic technologies to enable new missions [1]. Hypersonic vehicles are supposed to revolutionize the way we travel on Earth, enabling high-speed point-to-point connections while at the same time they will facilitate space access with reusable systems. In the latest years, the scientific community has been focusing on the technical feasibility of hypersonic flights while very few studies were aimed at assessing the economic sustainability of such initiatives. Indeed, in the field of high-speed transportation systems, the most widely used model is the TRANSCOST model [2–4], which dates back to the '70s and it is an admirable example of the formalization of cost estimation methodology for very innovative concepts. This cost model was conceived to assess the economic viability of launch vehicles and it provides a valuable starting point to investigate the potential of new launching systems [5]. However, the application of the original TRANSCOST model to estimate the life-cycle cost of a hypersonic case is not straightforward, as highlighted in Ref. [6], where an in-depth literature review confirmed the possibility to use TRANSCOST model as baseline for the development of brand-new equations for the Research, Development, Test and Evaluation (RDTE) as well as production (PROD) Cost Estimation Relationships (CERs). Conversely, the TRANSCOST formulation was not considered adequate to support the Direct and Indirect Operating Costs. As Direct Operating Costs (DOC) are concerned, suggestions for the extension of classical cost estimation methodologies to hypersonic applications exist and are based on modified versions of the models proposed by Air Transport Association of America (ATA) [7], by the Association of European Airlines (AEA) [8], and by Liebeck [9]. In this context, NASA synthetized all the efforts and suggested a more generic approach, specifically tailored towards the future hypersonic transportation systems [10], which has proved to be a valuable starting point [6].

Besides the evident need to update the statistical population and consequently, the mathematical formulation of the CERs already available in literature, it is uttermost important to establish a direct link with the most recent conceptual design methodologies. Indeed, the worldwide flourishing research activities in the field of hypersonics, is characterized by a wide spectrum of vehicle configurations, mission scenarios, propulsive technologies and subsystems configurations, which shall be properly represented into the cost model to eventually evaluate their impact onto the vehicle life-cycle cost and, at last, onto

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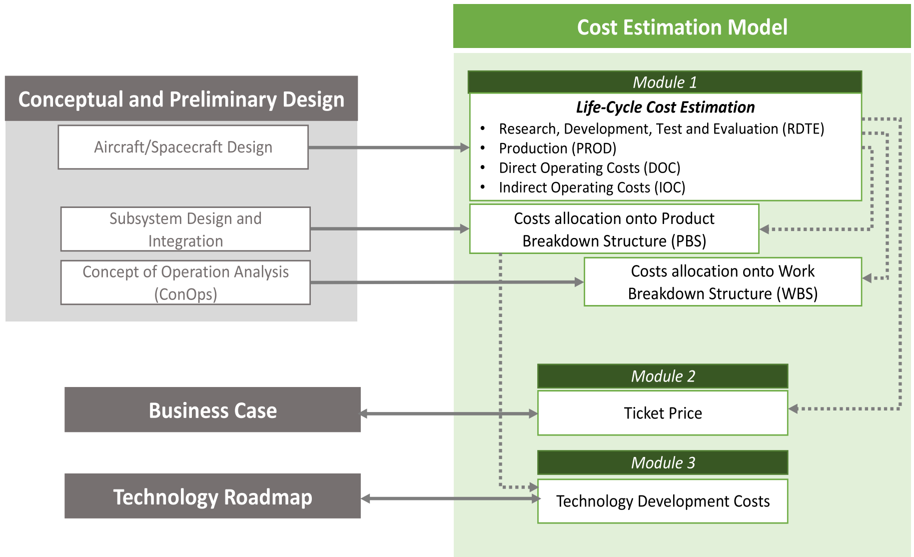

Fig. 1. Cost Estimation Model contents and connections with the other early design investigations.

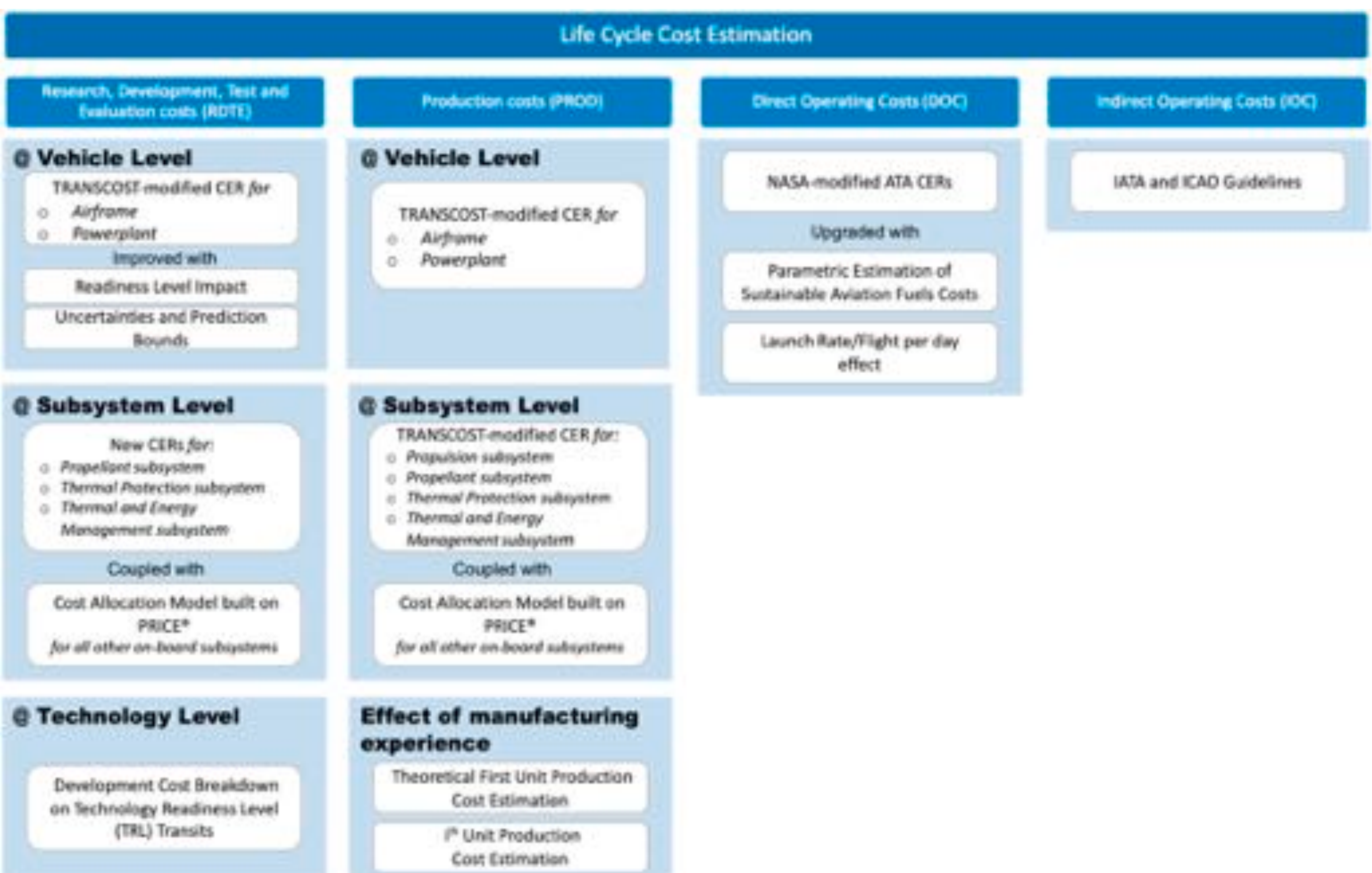

Fig. 2. Life Cycle Cost estimation model for hypersonic vehicles.

the ticket price. The establishment of a direct link with the design methodology can be envisaged at different levels. In fact, the connection with the results of the conceptual design activities allows for the integration of vehicle design and operational parameters (in addition to the mass) into the mathematical cost formulations, as cost drivers. Beyond that, the establishment of a direct link to the preliminary design activities enables cost estimations at subsystem level, and the allocation of vehicle-level costs on the constituent subsystems, equipment and components (the so-called allocation onto the Product Breakdown Structure). In this paper, special attention is devoted to the formalization of CERs targeting key-enabling subsystems of a hypersonic vehicle, including combined cycle engines and multi-functional subsystems.

Complementary, as already highlighted in Ref. [11], the available statistical population for hypersonic vehicles can be meagre and

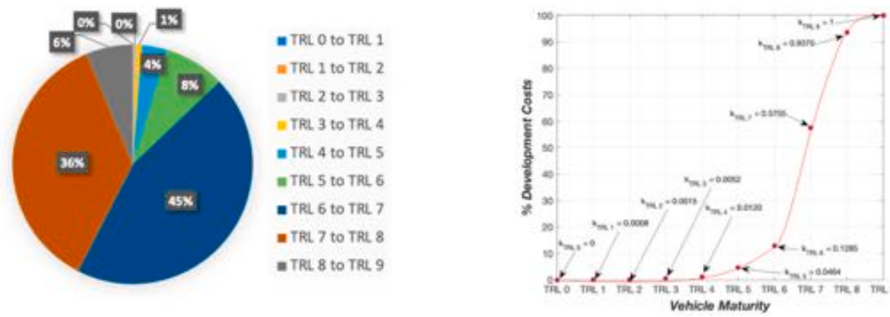

Fig. 3. RDTE Cost for each TRL transit (left) and percentage development cost as function of the vehicle maturity (right).

dispersed. For this reason, it is essential to assess the uncertainties on the original data and to formalize a procedure to allocate these uncertainties onto the various cost items, up to the results in terms of vehicle life-cycle cost or ticket price. Therefore, the new cost estimation formulation here presented is complemented with prediction margins accounting for the uncertainties on the data-driven correlations.

Lastly, it is worth underlying that all the methodologies available in literature, including the most recent formulation attempts, only partially include the possibility to tackle under-development technologies, simply by means of arbitrary development difficulties factors, without a clear and rational justification [12,13]. To overcome this shortcoming, this paper suggests a generic formulation to introduce the Technology Readiness Level (TRL) as cost driver in the RDTE CERs. This improvement paves the way for the exploitation of the cost model along the Technology Roadmapping process, where for every key-enabling technology, an incremental development path consisting of research and experimental activities is proposed, along with an estimation of the economic and time resources request [14–19].

Fig. 1 graphically summarizes the contents of the Cost Estimation Model developed by Politecnico di Torino, highlighting the multiple connections established with the other activities carried out during the early design phases of a complex and advanced system like a hypersonic vehicle. All the three modules of the parametric cost estimation model have been refined and exploited in the context of the Horizon 2020 STRATOFLY project (2018–2021), where the technological, operational, environmental, and economic viability of a Mach 8 waverider concept has been investigated [20,21]. Specifically, this paper focuses on the development and production cost formulation included in Module 1. In line with the most recent Business Cases analyses, an expected ticket price as expensive as a first-class subsonic long-haul flight is obtained, thus confirming the economic viability of the under-development concept.

2. Parametric cost estimation model development

2.1. Methodology overview

In the Introduction, the results of the in-depth literature review are reported. From this preliminary analysis the need to set up a new cost estimation model specifically tailored on hypersonic vehicles is vital to assess the economic sustainability of the under-development solution. In fact, to meet the needs of the different stakeholders, which may have an interest in economically assessing the potential of a high-speed vehicle, the methodology reported in this section clearly shows some novelties with respect to what is available in literature. Specifically, the new parametric cost estimation model moves beyond the state-of-the-art methodology (1) by integrating vehicle design and operational parameters (in addition to the mass) as cost drivers for the prediction of the vehicle life-cycle cost, (2) by introducing prediction margins accounting for the uncertainties on the data-driven correlations, (3) by providing a first estimate of the costs of every on-board subsystem, including combined cycle engines and multi-functional subsystems, (4) by increasing the granularity of the analysis up to technology level, thus providing a valuable support to Technology Roadmaping activities.

According to Fig. 2, the life-cycle cost estimation of a hypersonic vehicle can be decomposed in four major cost categories (or sources as referred to in Ref. [22]): RDTE, PROD, DOC and IOC. As already anticipated into the introduction section, the literature analysis clearly highlights the unavailability of a comprehensive model specifically tailored for hypersonic vehicles. Therefore, depending on the specific cost category, different approaches have been pursued to develop the Cost Estimation Relationships. In some cases, already available CERs have proved to be able of predicting costs associated to a hypersonic population, whilst in other cases, modified or brand-new relationships have been formulated and adopted. Details on the CERs development are provided per each cost category in the following subsections.

2.2. RDTE costs

Hypersonic vehicles may be considered as future high-speed transportation on Earth as well as future reusable first stages of access-to-space and re-entry systems. Therefore, as already envisaged by Koelle at the time of the Sänger project [2,3], RDTE and production costs models developed to support cost estimation of future reusable launch vehicles can be adopted as baseline for a new set of equations specialized for the hypersonic point-to-point transportation. Most of the tuning coefficients represented as f_i, are included in the formulations provided within this paper using the same definition reported in the original TRANSCOST model. However, when they implicitly include a dependency from a design or mission variable, the explicit form has been preferred. It is also worth mentioning that, as already highlighted in Ref. [11], the available statistical population for hypersonic vehicles is usually meagre and dispersed, thus it is essential to assess the uncertainties on the original data and to formalize a procedure to allocate these uncertainties onto the various cost items. Therefore, the new cost estimation formulation presented in the following sections can be complemented with prediction margins accounting for the uncertainties on the data-driven correlations, using the results of the prediction intervals estimation in Ref. [11].

2.2.1. Vehicle level

As far as RDTE cost category is concerned, the equations suggested by TRANSCOST have been used as basis at vehicle level, where according to Koelle[4], the development cost can be simply split into the airframe (including all subsystems) (H_{VA}) and the powerplant contributions (H_{ET}, H_{ER}, H_{CCE}). With respect to the original equation provided in TRANSCOST, the total development cost of for a high-speed vehicle equation (Eq. (1)) is enhanced with (i) the capability of estimating the cost at completion on the basis of the current technological maturity level and (ii) a cost escalation factor $\frac{(CPI)_{year}}{(CPI)_{2016}}$ to guarantee updated estimations. As far as the first upgrade is concerned, the original formulation allows estimating the cost associated to the entire development path

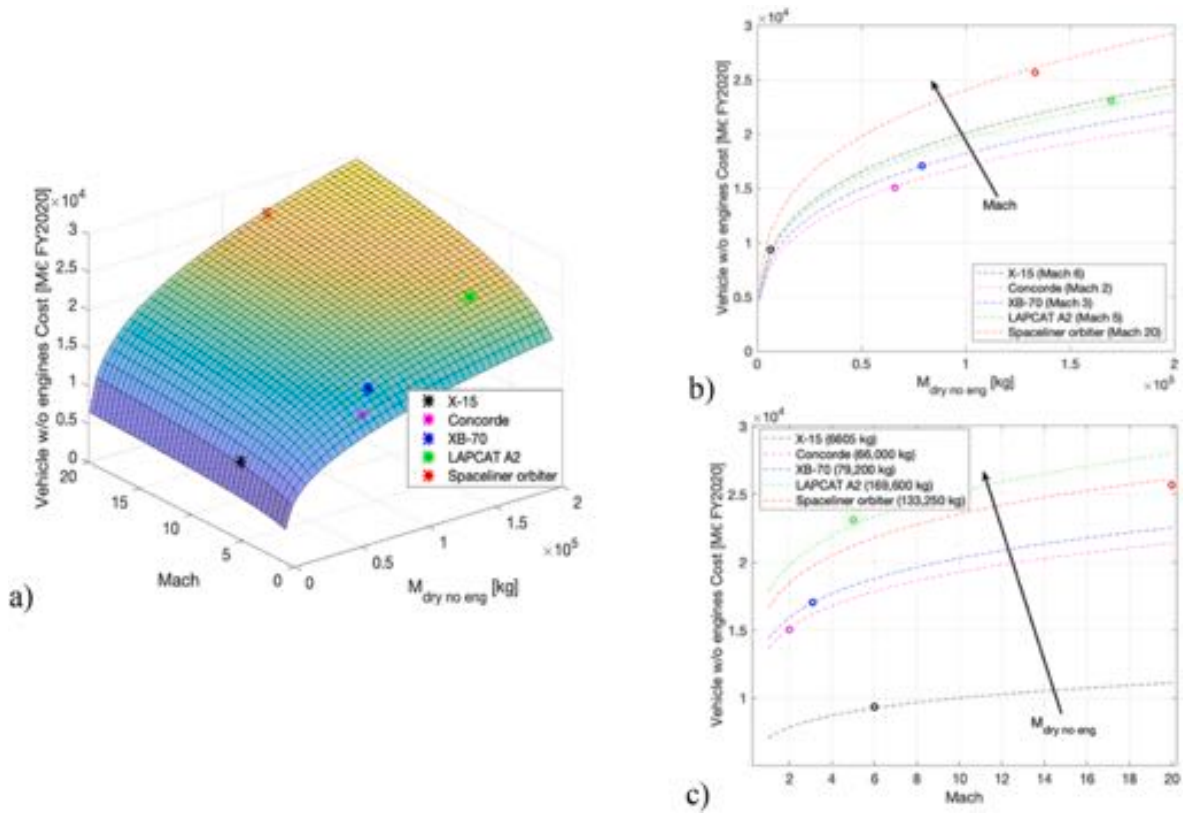

Fig. 4. a) 3D Construction of the Vehicle (w/o Engine) RDTE CER (Eq. (2)) with a hypersonic dataset; b) 2D Variation of the Vehicle (w/o Engine) Cost as function of the vehicle dry mass (w/o Engine) using Mach number as parameter; c) 2D Variation of the Vehicle (w/o Engine) Cost as function of the Mach number using vehicle dry mass (w/o Engine) as parameter.

of the vehicle, from TRL 0 to 9. This is a conservative approach perfectly fitting the purposes of a conceptual design stage. However, to avoid overestimations, the vehicle level RDTE cost formulation has been enriched with a parameter which allows to evaluate the real expected costs depending on the average maturity of the system. Intuitively, a factor accounting for the vehicle maturity can be introduced in the form $(1 - k_{TRL})$, where the k_{TRL} factor shall vary from 0 for an average TRL to 1 for an average TRL of 9. However, the estimation of k_{TRL} for intermediate maturity levels requires to understand the distribution of Vehicle Cost at Completion (CaC) on TRL transits. In the literature [18], a first attempt of CaC distribution on TRL transits for hypersonic and re-entry space transportation systems has been performed mainly thanks to experts' opinion. In this context, a new semi-empirical model is suggested based on historical cost data, coming from the Space Shuttle programme. The Space Shuttle is the only reusable hypersonic system for which complete cost data are available [23,24]. Then, in order to distribute the available costs on TRL transits, TRL milestones have been distributed along the timeline of Space Shuttle development program. The association of TRL milestones along the timeline allows to suggest a new Vehicle CaC distribution on TRL transits to be compared with the original CaC distribution from Ref. [25]. From this activity it has been clear that the Cost at Completion for a generic hypersonic vehicle with a point-to-point mission is composed of the development cost up to TRL9, the production cost of the first unit and eventually the initial operating costs associated to the very first flight tests. On the basis of the Life Cycle Cost (LCC) assessment presented in Ref. [6] and the results of the Vehicle CaC distribution on TRL transits, the RDTE breakdown reported in Fig. 3 is obtained. The percentages presented in this Fig. 3 can be generically applied to similar high-speed vehicle concepts. The results are in line with the original [18], confirming that great part of development costs of hypersonic are related to TRL transits from 6 to 7 and from 7 to 8, when flight demonstrators are designed, produced and tested.

The vehicle development cost equation is reported in Eq. (1), where, $C_{TOT_{dev}}$ is the RDTE cost of the entire high-speed vehicle in [M€]; k_{TRL} is a factor accounting for the vehicle maturity and it varies from 0 for an average TRL 1 to 1 for an average TRL of 9; H_i is the cost of the item (i.e. airframe or engine) in [WYr]; f_0 is the systems engineering integration factor (1.04 , *as TRANSCOST suggests*); f_6 is a factor accounting for the deviation from optimal schedule (1 for on-time and up to 1.6 for heavy delays); f_7 is the program organization factor ($n_{subco}^{0.2}$); f_8 is defined as the impact of region productivity (1 for USA, 0.86 for Europe, 1.2 for China, 1.5 to 2.1 for Russia); $(CPI)_{year}$ is the Consumer Price Index of the reference year for the cost estimation; $(CPI)_{2016}$ is the Consumer Price Index of the data from literature, i.e. $(CPI)_{2016} = 240.01$; and the factor 0.3102 allows to move from Wyr to M€.

$$C_{TOT_{dev}} = \left[(1 - K_{TRL}\right) f_0^{n_{stages}} \left(\sum_{i=1}^{N_{items}} H_i\right) f_6 f_7 f_8\Big] \, 0.3102 \frac{(CPI)_{year}}{(CPI)_{2016}} \quad (1)$$

2.2.1.1. Vehicle (w/o engines) RDTE CER. According to TRANSCOST model, the first component of the overall vehicle development cost is the airframe (with subsystems), which is here labelled as vehicle without engines. In this case, the trend proposed by the original model have been critically assessed with respect to a set of more recent data about on-going high-speed projects. Specifically, the update of the statistical population brings to a new formulation of the parametric equation, mainly in terms of numerical coefficients, rather than in the form of the equation itself. As clearly shown in Fig. 4, the predictions resulted to be in good agreement with historical data with a proper tuning of all equation parameters. Particularly, with respect to the original formulation of Eq. (2), f_{10} (reduction factor due to experience/cost engineering) and f_{11} (reduction factor due to absence of government contracts) parameters have been neglected as they are not directly applicable to the

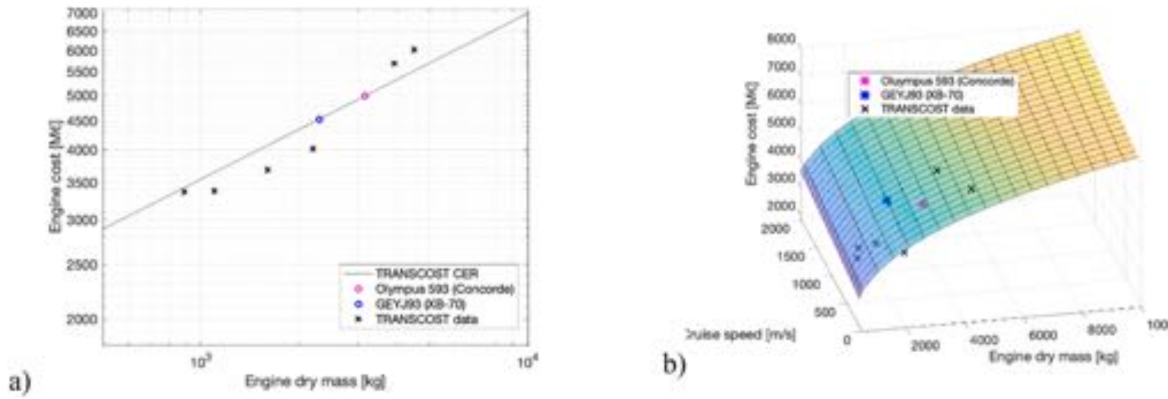

Fig. 5. a) Validation of the original TRANSCOST CER (dependence from engine dry mass only) with two new points; b) TRANSCOST modified low-speed engine RDTE CER (Eq. (3)) including dependence from engine dry mass and engine speed.

case under investigation and too difficult to be estimated. Moreover, to better reveal the dependency of this cost item with respect to the cruise Mach number, the f_2 parameter has been explicitly inserted in the CER, as $\mathscr{M}ach^{0.15}$, as visible in Eq. (2).

$$H_{VA} = 1746\, M_{dry_{no-eng}}^{0.284}\ \mathscr{M}ach^{0.15} f_1 f_3 \tag{2}$$

where: H_{VA} is the vehicle without engines development cost [WYr]; $M_{dry_{no-eng}}$ is the dry mass of vehicle without engines [kg]; f_1 is the development standard factor (from 0.3 for a variation of an existing project; to 1.4 for a new concept involving new techniques and technologies); and f_3 is the team experience factor in the range (from 0.5 for extended experience; to 1.4 for new team with no experience).

2.2.1.2. Engines RDTE CER. While formulations for rocket engines are already available in literature, and considering the case studies targeted in this publication, only airbreathing engines are considered in this subsection. In details, past and more recent research activities clearly show that future civil hypersonic aircraft will opt for one of the following two main propulsive options.

o **on-board installation of two independent propulsive subsystems**, one able to support "**low-speed**" operations, extending from subsonic to low supersonic speed regimes and a second one able to support "**high-speed**" phases, thus accelerating the vehicle up to and allowing cruise at hypersonic speed. As a "low-speed" engine, one of the following alternatives can be selected:

- Turbojet or turbofan without afterburner
- Turbojet or turbofan with afterburner
- Pre-cooled turbojet or turbofan with afterburner

Complementary, the "high-speed" engines family encompasses.

- Ramjet
- Scramjet
- Dual mode ramjet

o **Integration of "low-speed" and "high-speed" capabilities in a Turbine-Based Combined Cycle (TBCC) engine.** Those engines can be classified in two groups depending on the integration of the turbojet and the ramjet engines:

- Tandem TBCC engines:

- (Pre-cooled) turbojet or turbofan with afterburner where a bypass flow can get around the low speed combustor & turbine to use the afterburner combustor as a ramjet combustor for high speeds (- > e.g. SR-71 engine)
- GGC-ATR (Gas Generator Cycle - Air Turbo Rocket/Ramjet)
- EXC-ATR (EXpander Cycle - Air Turbo Rocket/Ramjet)

- Upper/Lower or Side/Side TBCC engines: The flow can be divided in two clearly separated engines:

- One belonging to the turbojet family or the tandem TBCC family
- One belonging to the ramjet family

Unfortunately, the lack of historical cost data for all these propulsive systems architectures has prevented the authors from suggesting details CER formulations ad-hoc customized for each variant. However, the crucial role of propulsive systems for future civil high-speed aircraft requires to provide at least a first guest estimate for their development cost. Therefore, hereafter, the authors disclose two different approaches for the estimation of engines RDTE costs. The two approaches share a parametric formulation, but they are characterized by a different level of details and thus of fidelity levels.

The first approach better fits conceptual design needs, where only the general propulsive subsystem layout is expected to be defined, and only few details might be available. In this case, three different formulations have been developed, one for "low-speed" engines, one for "high-speed" engines and one for "combined cycle engines". It is worth noting that even if the disclosed equations are not developed to describe a specific engine technology, they can be tailored by the users to better reply to their needs thanks to specific parameters included into the formulations. In detail, Eq. (3) and Eq. (4) are suggested for propulsive subsystem configurations in which a low-speed engine and a high-speed engine (ramjet or scramjet) can be identified.

As far as the low-speed air-breathing engine is concerned, the original formulation provided by TRANSCOST is well fitting the low-speed engines cost data (see Fig. 5a), including two additional points here used for validation, i.e. the Olympus 593 engine (of the Concorde) and the GEYJ93 engine (of the XB-70). However, differently from the original formulation, Eq. (3) includes a second term in which the dependence from the engine maximum operating speed is introduced. In this way, the original formulation is modified suggesting the dependence on a new operational parameter, in addition to the operative empty weight already present (Fig. 5b).

$$H_{ET} = \left(1380 M_{dry_{ET}}^{0.295} + 1.12v\right) f_1 f_3 \tag{3}$$

where H_{ET} is the low-speed engine RDTE cost in [WYr]; $M_{dry_{ET}}$ is the dry mass of the reference engine [kg]; and v is the maximum engine speed [m/s].

It is wort noting that considering the available dataset (TRANSCOST

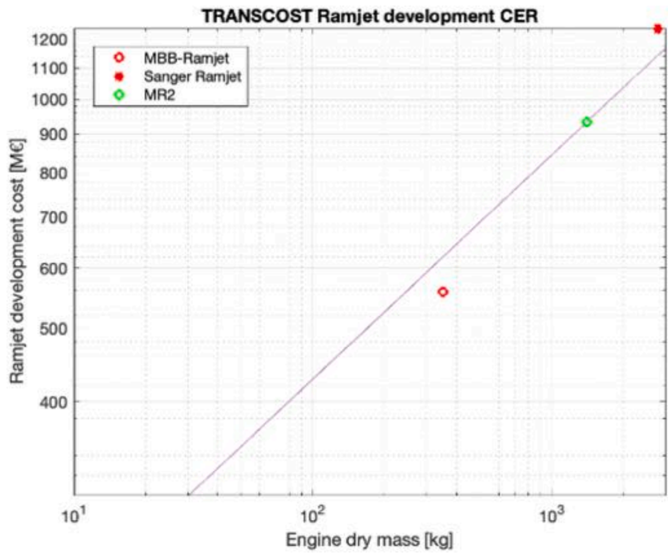

Fig. 6. High-speed engine RDTE CER (Eq. (5)) by TRANSCOST.

plus new points), the validity of Eq. (3) is confirmed for engines having a dry mass between 500 kg and 10,000 kg.

As far as the high-speed engine is concerned, the original TRANSCOST formulation reveals to be valid for new engine concepts as reported in Fig. 6a. Thus, it can be included into the parametric model without further changes, as reported in Eq. (4)

$$H_{ER} = 355 M_{dry_{ER}}^{0.295} f_1 f_3 \tag{4}$$

However, as stated at the beginning of this subsection, the latest high-speed aircraft concepts envisage TBCC engines technologies. In this case, Eq. (5) has been developed to support the RDTE cost estimation of combined-cycle engines, i.e. when the same unit can operate in different speed regimes. The formulation is a combination of the low-speed and high-speed equations reported in Eq. (3) and Eq. (4), enriched with the possibility to better customize the estimation, on the basis of a numerical parameter, hereafter called complexity factor. The final CER can be calculated as follows (5):

$$H_{CCE} = C_{complexity} \left(k_{TJ} H_{ET} + k_{RJ} H_{ER}\right) f_1 f_3 \tag{5}$$

where H_{CCE} is the Combined Cycle Engine RDTE cost [WYr]; k_{TJ} and k_{RJ} are the low-speed and high-speed 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; and $C_{complexity}$ is a multiplication factor used to compare the considered design to an existing one (i.e. it can be exploited as escalation or reduction cost factor depending on the global configuration of the considered engine).

The second approach better fits preliminary and detailed design needs, where geometrical and constructional details are known as well as the expected performance throughout the operating cycle. In line with what is available in literature, like for example, Vought methodology [26], more complex formulations can be derived, following a bottom-up approach. In this case, RDTE and production cost per engine unit is estimated as a lumped sum of different cost components and production processes contributions. However, the implementation of such a cost methodology goes beyond the scope of this paper. As a future work, the systematic application of this second approach to a wide set of engines architectures, in an already advanced stage of design, can be the basis for data collection and surrogate models' development, becoming a starting point for the definition of a future set of more specialized CERs for the propulsion subsystem.

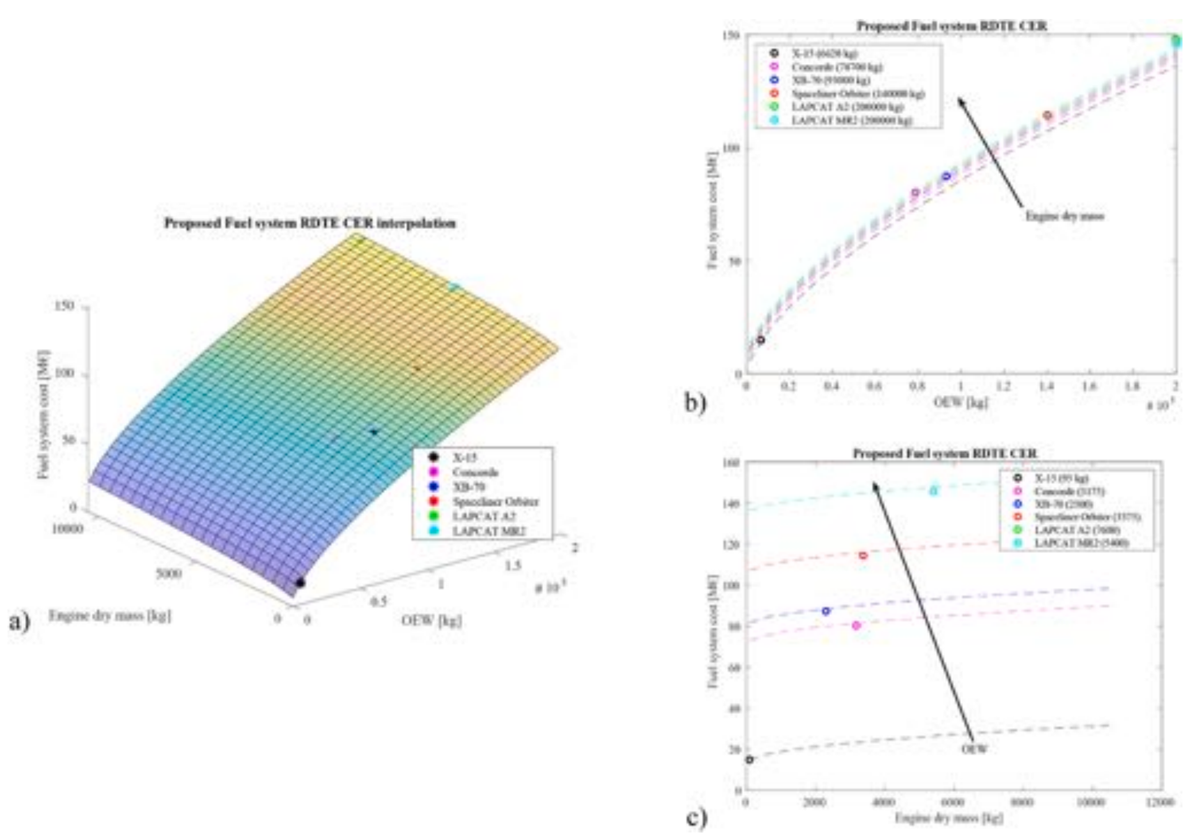

Fig. 7. a) Propellant (or Fuel) RDTE CER; b) Variation of the Propellant RDTE Cost as function of the operative empty weight (OEW) using the engine dry mass as parameter; c) Variation of the Propellant RDTE Cost as function of the engine dry mass using the OEW as parameter.

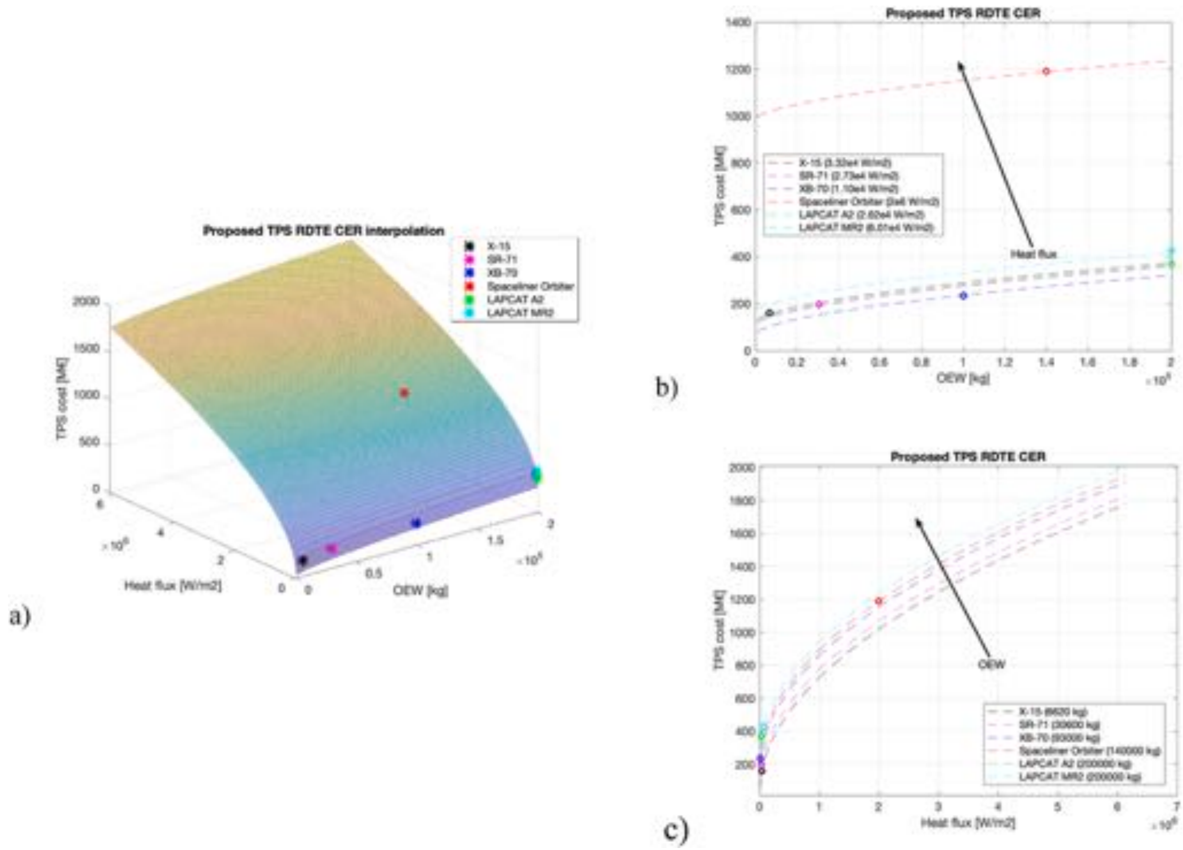

Fig. 8. a) TPS RDTE CER; b) Variation of the TPS RDTE Cost as function of the operative empty weight (OEW) using the heat flux as parameter; c) Variation of the TPS RDTE Cost as function of the heat flux using the OEW as parameter.

2.2.2. *Subsystems level*

The need to establish a link with design activities requires to increase the level of granularity of the cost estimation model, thus moving from vehicle to subsystems level. At this stage, considering the unavailability of parametric formulations for specific subsystems (except for engines), a hybrid approach is suggested. Considering that historical cost data are insufficient to define complex parametric equations, subsystems costs can be suggested as percentage of the vehicle total RDTE. These percentages have been obtained by the authors through a detailed modelling of three hypersonic vehicles (namely, the LAPCAT A2, the LAPCAT MR2.4 basic and LAPCAT MR2.4 all electric versions) following the exploitation of PRICE-H Model [25] included within commercial tools. Each cost item of the detailed Product Breakdown Structure (PBS), i.e. each subsystem, has been modelled according to PRICE-H Model by means of parameters representing the complexity, the innovation level and the technology behind the subsystem itself. The tuning of the numerical values associated to each parameter has been finalized, by implementing at first the LAPCAT A2 case study, for which ESA provided reference cost data coming from previous independent studies based on [4] and on [27,28]. Then, the LAPCAT MR2.4 case study has been defined as "improved configuration" with respect to the baseline (i. e. LAPCAT A2). This assumption perfectly represents the historical background of the LAPCAT II project as summarized in Ref. [29]. This approach has been useful on one side to suggest subsystem costs as percentages with respect to the overall RDTE and on the other side to create a cost database for a limited number of case studies for the most cost-impacting subsystems. Specifically, for the propellant subsystem, the thermal protection subsystem and the thermal and energy management subsystem the cost data obtained exploiting the PRICE-H model has been used to suggest new mathematical formulations. Among all the possible subsystems, the three mentioned above have been selected for the generation of a real CER (and not just a percentage), because it was possible to identify main drivers for the equations, as it is reported in the next subsections.

2.2.2.1. *Propellant subsystem RDTE CER.*

The CER for fuel/propellant system development is not available in literature. Therefore, thanks to the availability of a set of cost data for high-speed vehicles built using PRICE-H Model and following the generic CER formulation suggested in TRANSCOST, the parametric formulation reported in Eq. (6) is defined. For this subsystem, three main drivers are considered: the vehicle operative empty weight, the engine dry mass, and the type of fuel.

$$S_{prop_{dev}} = \left(0.1 M_{OEW}^{0.68} + 0.50 \rho_F^{-0.60} + 0.49 M_{E_{dry}}^{0.51}\right) f_1 f_3 \tag{6}$$

Where $S_{prop_{dev}}$ is the is the development cost for the propellant subsystem [WYr]; $M_{E_{dry}}$ is the sum of the engines dry masses [kg] (e.g. 1 ATR+ 1 DMR); M_{OEW} is the Operative Empty Weight (OEW) [kg]; and ρ_F is the fuel density [kg/m3].

The application of powerplant dry mass as additional driver allows scaling the cost of the system depending on the size and complexity of the propulsive architecture. The formulation reported in Eq. (6) is derived based on the interpolation reported in Fig. 7. As it can be seen the main contribution is due to the OEW since it represents the size of the vehicle, even if the dry mass of the powerplant allows tuning the final results.

2.2.2.2. *Thermal protection subsystem RDTE CER.*

A similar approach is applied to derive the CER related to the Thermal Protection System (TPS) development. In this case, in addition to the OEW, the maximum expected heat flux along the mission is included as cost driver (Eq. (7)).

The resulting trend is reported in Fig. 8a. The contributions of the

Table 1
Percentage breakdown of a hypersonic cruiser RDTE costs.

Cost Items	Cost as percentage of Vehicle RDTE	
Propellant subsystem	0.4%	Vehicle w/o engines RDTE 78.2% of RDTE
Thermal Protection Subsystem (TPS)	2.8%	
Thermal and Energy Management Subsystem (TEMS)	0.2%	
Integration	17.8%	
Structure	47.1%	
Landing Gear	0.4%	
Environmental Control Subsystem (ECS)	1.6%	
Ice Protection Subsystem (IPS)	0.5%	
Fire Protection Subsystem (FPS)	0.6%	
Flight Control Subsystem (FCS)	2.2%	
Avionic Subsystem	0.7%	
Electrical Power Subsystem (EPS)	2.6%	
Water Subsystem	0.4%	
Oxygen Subsystem	0.4%	
Lights Subsystem	0.2%	
Furnishing	0.3%	
Low-Speed Engine	18.6%	Engines RDTE 21.8% of RDTE
High-Speed Engine	3.2%	

two cost drivers are in this case more balanced than in the propellant system CER, even if the heat flux is now the main parameter. This is reasonable considering the nature of the system under design.

$$S_{TPS\,dev} = \left(0.56M_{OEW}^{0.59} + 1.8q^{0.51}\right)f_1 f_3 \quad (7)$$

Where $S_{TPS\,dev}$ is the development cost for the TPS [WY] and q is the reference design heat flux considered for the vehicle TPS [W/m^2]. Specifically, for the proposed work, the reference heat flux is computed at the stagnation point, for the different aircraft, in most critical conditions (maximum value encountered along the mission profile), considering that the wall temperature is evaluated in radiative equilibrium conditions, as specified in Refs. [30,31]. The choice of this reference value for the heat flux is justified by the need of identifying a sort of "class" in terms of TPS performance that has to be designed and developed in order to ensure vehicle concept feasibility and safe flight within the expected operational environment. This was considered a reasonable assumption to catch the relevant information required to estimate the cost of the system, especially considering development phase.

2.2.2.3. Thermal and energy management subsystem RDTE CER. High-speed aircraft are unique example of highly integrated systems, as demonstrated by the Thermal and Energy Management System (TEMS) concepts [32,33], which integrates Propulsive, Fuel, Thermal Control, Thermal Protection, Electrical and Environmental Control Systems, especially in case of adoption of cryogenic propellants. For the concept specified in Refs. [32,33], taken as reference in this work for the development of the associated CER, the heat loads which penetrate the aeroshell generate boil-off within the cryogenic tanks. The boil-off line collects hydrogen vapours from the different tanks to use boil-off hydrogen as coolant mean for different loads prior to be injected into the combustion chamber of the propulsion plant. The liquid hydrogen line transfers the propellant from the auxiliary tanks to the primary ones to feed the engines. The high-pressure liquid hydrogen cools the propulsion plant in the cooling jacket, and it is then expanded through a turbine to provide mechanical power and subsequently electrical power. The turbine drives in fact both the boil-off compressor and the electrical generator.

The TEMS concept, as specified in Refs. [32,33], is a very peculiar system because of the extreme integration of its own functionalities. In order to sketch a possible cost trend, the application of TEMS to A2 is

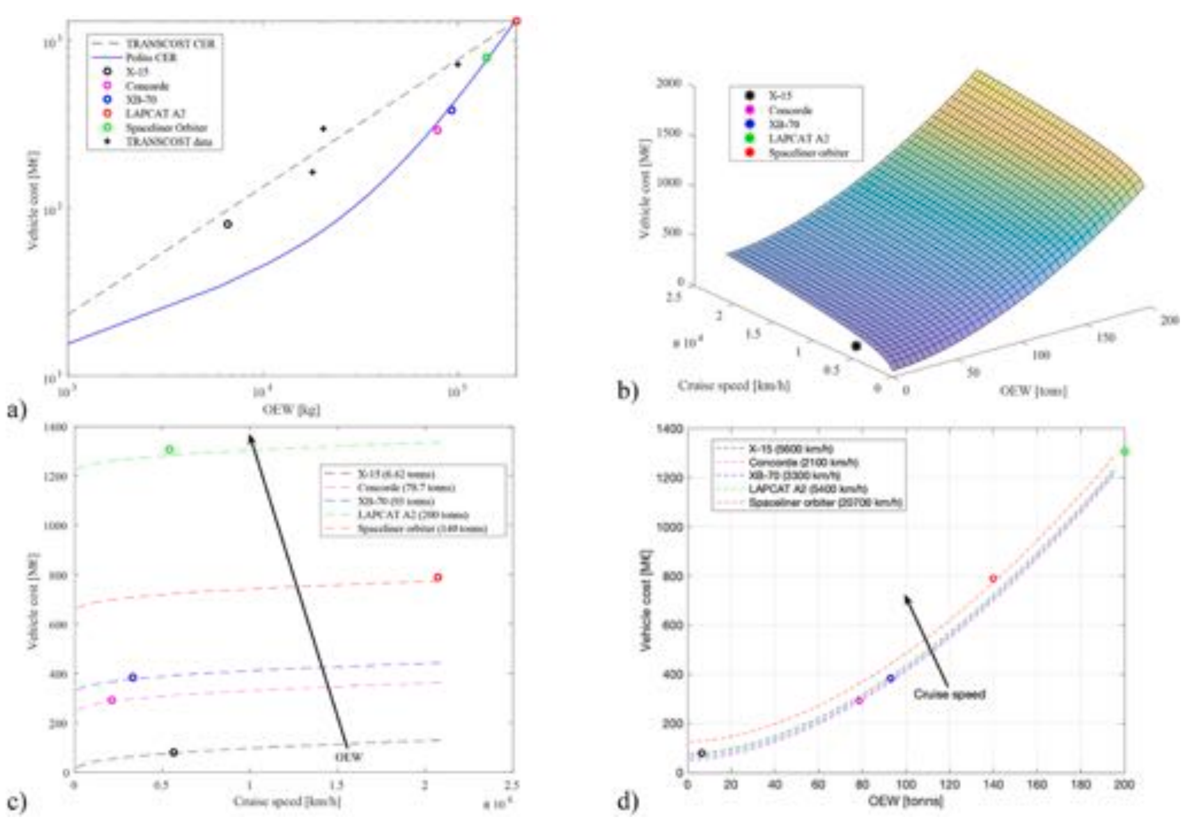

Fig. 9. a) Comparison of the Vehicle without engines PROD cost CER disclosed by POLITO and the original one; b) 3D Vehicle without engines PROD cost CER (updated formulation); c) Vehicle without engines PROD cost as function of the cruise speed and using the Operative Empty Weight as parameter (updated formulation); d) Vehicle without engines PROD cost as function of the Operative Empty Weight and using the cruise speed as parameter (updated formulation).

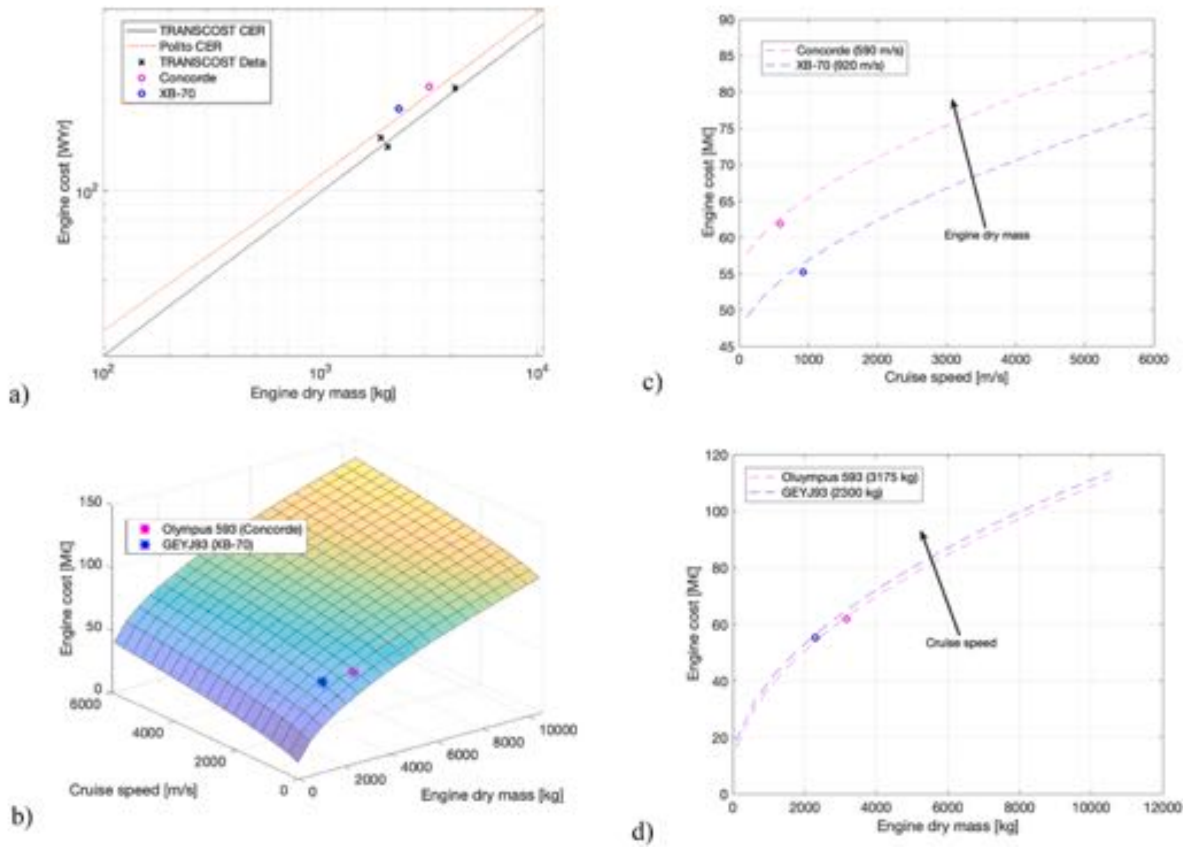

Fig. 10. a) Upgrade of the original TRANSCOST formulation to better represent the engine cost dependency from the engine dry mass; b) 3D low-speed engine PROD cost CER including dependency from speed; c) Low-speed engine PROD cost as function of the cruise speed and using the engine dry mass as parameter; d) Low-speed engine PROD cost as function of dry mass and using cruise speed as parameter.

simulated. The final cost is computed basing on some of the main operating parameters of the system under design and, notably, generated power and boil-off flow rate (together with the OEW, as always). The final CER, valid only for a specific architecture, similar to the one proposed in Refs. [32,33], is reported in (8) and revels the impact of power and hydrogen flow rate onto the development cost of this subsystem, in addition to the Operative Empty Weight.

$$S_{TEMS\,dev} = \left(5.73 M_{OEW}^{0.26} + 0.8 P^{0.17} + 0.53 \dot{m}_{H2}^{0.19}\right) f_1 f_3 \tag{8}$$

$S_{TEMS\,dev}$ is the development cost for the TEMS [WY]; P is the power generated by TEMS [W]; $\dot{m}$ is the mass flow of the reference driving fluid within TEMS cycle [kg/s].

For all other subsystems, PRICE-H model, properly customized to cover high-speed vehicles, is used to define a percentage costs breakdown of the overall vehicle development cost. It is worth noticing that for sake of clarity, Table 1 contains all subsystems, including those for which a specific parametric cost estimation is available.

2.3. Production costs

2.3.1. Vehicle level

The development of a parametric cost model to estimate production cost of a future high-speed aircraft follows the same approach described in Section 2.2 for development costs. In this case, the overall vehicle production cost can be estimated using Eq. (9), which apart from the cost escalation factor, is the one provided by TRANSCOST.

$$C_{TOT_{prod}} = f_0^{n_{stages}} \left(\sum_{i=1}^{n_{items}} F_i \right) f_8 \; 0.3102 \frac{(CPI)_{year}}{(CPI)_{2016}} \tag{9}$$

Where $C_{TOT_{prod}}$ is the total vehicle production cost; n_{stages} is the number of stages; f_0 is the systems engineering integration factor; f_8 is defined as the impact of region productivity (1 for USA, 0.86 for Europe, 1.2 for China, 1.5 to 2.1 for Russia); F_i is the production cost of the item (i.e. airframe or engine) in [WYr].

2.3.1.1. Vehicle (w/o engines) PROD CER. Following the approach applied to development costs, the analysis of existing TRANSCOST CERs is the starting point for the proposal of an updated formulation of the estimations of production costs. First of all, the original CER for the advanced high speed aircraft category production cost (in [WYr]) is evaluated, as reported in Eq. (10).

$$F_{VF} = \left(0.357 M_{OEW}^{0.762}\right) n_i^{\frac{\ln p}{\ln 2}} \tag{10}$$

This formulation includes the OEW as single cost driver, in [kg]. However, since the speed ranges for this category may vary a lot, a different correlation can be proposed, introducing flight speed within the equation, as shown in Fig. 9. Eq. (11) presents the new mathematical formulation.

$$F_{VF} = \left(0.34 M_{TOEW}^{1.75} + 7.06 v_{cr}^{0.4}\right) n_i^{\frac{\ln p}{\ln 2}} \tag{11}$$

Where F_{VF} is the vehicle without engines production cost in [WYr]; M_{TOEW} is the Operative Empty Weight [t]; v_{cr} is the vehicle maximum cruise speed [km/h]; n_i is the number of i-th unit produced; p is cost reduction percentage to be applied each time that the number of produced units doubles. This value is typically around 88–85% for aerospace industry.

Please, it is worth noting that the original TRANSCOST CER, as far as it is declared in the source, was built upon very few points which are

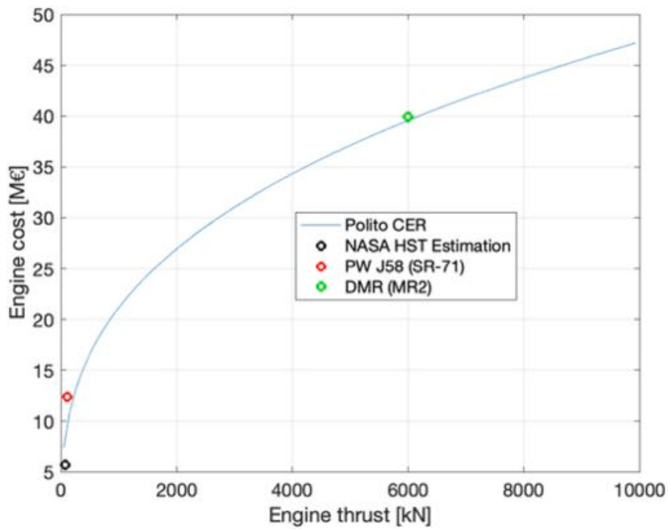

Fig. 11. High-speed Engine PROD cost.

suspected to be relatively old. Therefore, the authors believe that this original formulation may seriously suffer from data obsolescence, mainly since the production process of new high-speed aircraft has been revolutionized thanks to the introduction of new material, processes and technologies. A comparison of the two correlations is reported in Fig. 9a. The new trend (blue) fits quite well the most recent concepts used for the equation generation, especially in case of high OEW. However, the unavailability of vehicle cost data lower than $8 \bullet 10^4$ kg of OEW can suggest applying the updated formulation for higher OEW, while for lower values of OEW, a satisfactory equation is not yet available. Potentially, there is still a relevant deviation between the two relationships and, even if the authors are fully convinced that the introduction of the cruise speed (or, in general, of the design speed) is crucial for the identification of a more consistent production cost, considering the lack of additional data, the traditional TRANSCOST formulation (Eq. (10)) is kept as valid for the purpose of this work, also considering the example provided in Section 3. Still, Fig. 9 provides some insights of the new trend.

2.3.1.2. Low-speed engine PROD CER. Similar to the formulation proposed for the engine RDTE cost, the same approach is followed and the maximum operating speed of the engine is added as cost driver to better fit the available cost data. The results are reported in Fig. 10 and formalized in Eq. (12). Please notice that also in this case, the original formulation uses as single cost driver the engine dry mass. In this case, the additional data points have been used to better trim the cost dependency from the engine dry mass (see Fig. 10a) as well as to add the dependency from the operating speed in the formulation (see Fig. 10b, c, and d). Specifically, in Eq. (12), F_{ET} is the low-speed engine in [WYr]; v is the maximum operative speed of the engine [m/s]; n_i is the number of i-th unit produced; p is cost reduction percentage to be applied each time that the number of produced units doubles. This value is typically around 88–85% for aerospace industry.

$$F_{ET} = \left(2.29 M_{dry\ TJ}^{0.53} + 0.5 v^{0.6}\right) n_i^{\frac{\ln p}{\ln 2}} \tag{12}$$

2.3.1.3. High-speed engine PROD CER. No equation for ramjet production cost estimation is provided in TRANSCOST due to lack of data. Additional literature survey on available cost data [27] reveals that production cost of high-speed engines can be also associated to the maximum generated thrust in cruise conditions. Following this approach, Eq. (13) can be derived

$$F_{ER} = \left(5.63 T_{RJ}^{0.35}\right) n_i^{\frac{\ln p}{\ln 2}} \tag{13}$$

Where F_{ER} is the high-speed production cost; T is the ramjet thrust in [kN].

Fig. 11 reports the proposed new CER for high-speed engines, which is unfortunately based on three main points only. Other three points

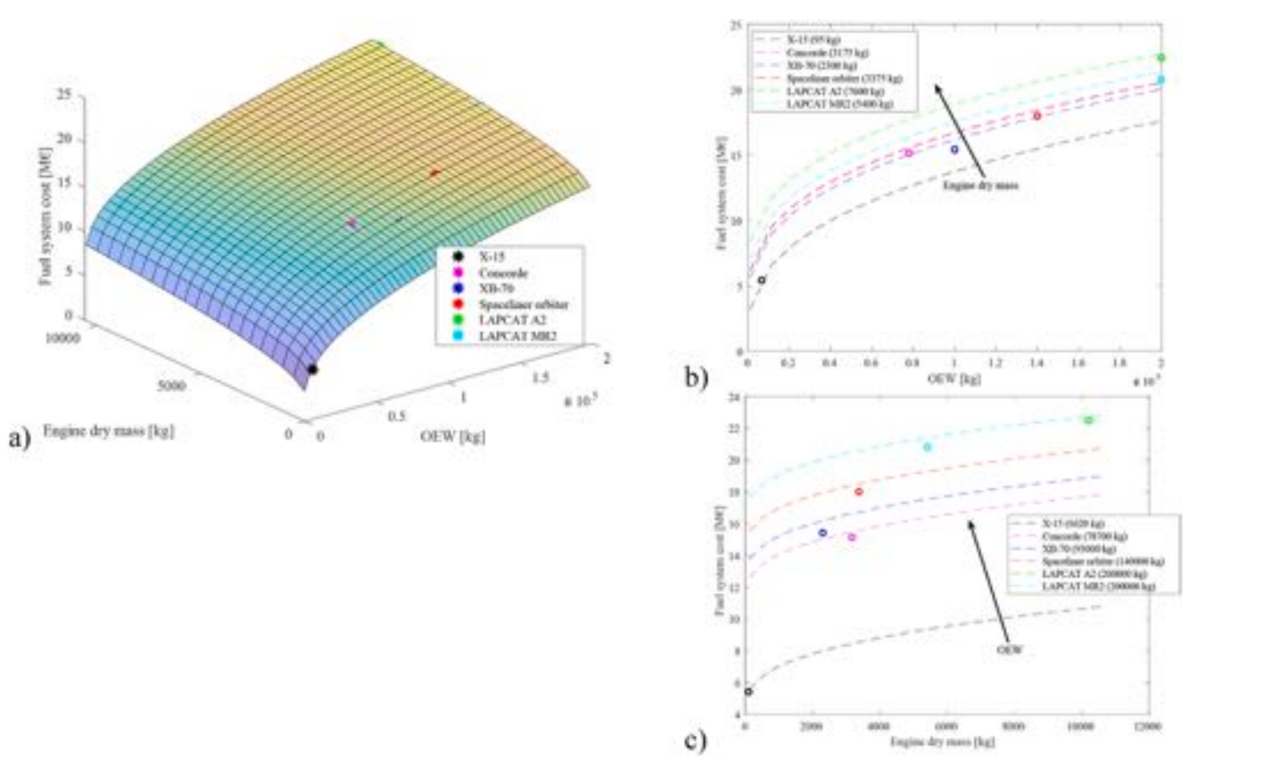

Fig. 12. a) 3D Propellant subsystem PROD cost CER; b) Propellant subsystem PROD cost as function of the OEW and using the engine dry mass as parameter; c) Propellant subsystem PROD cost as function of the engine dry mass and using OEW as parameter.

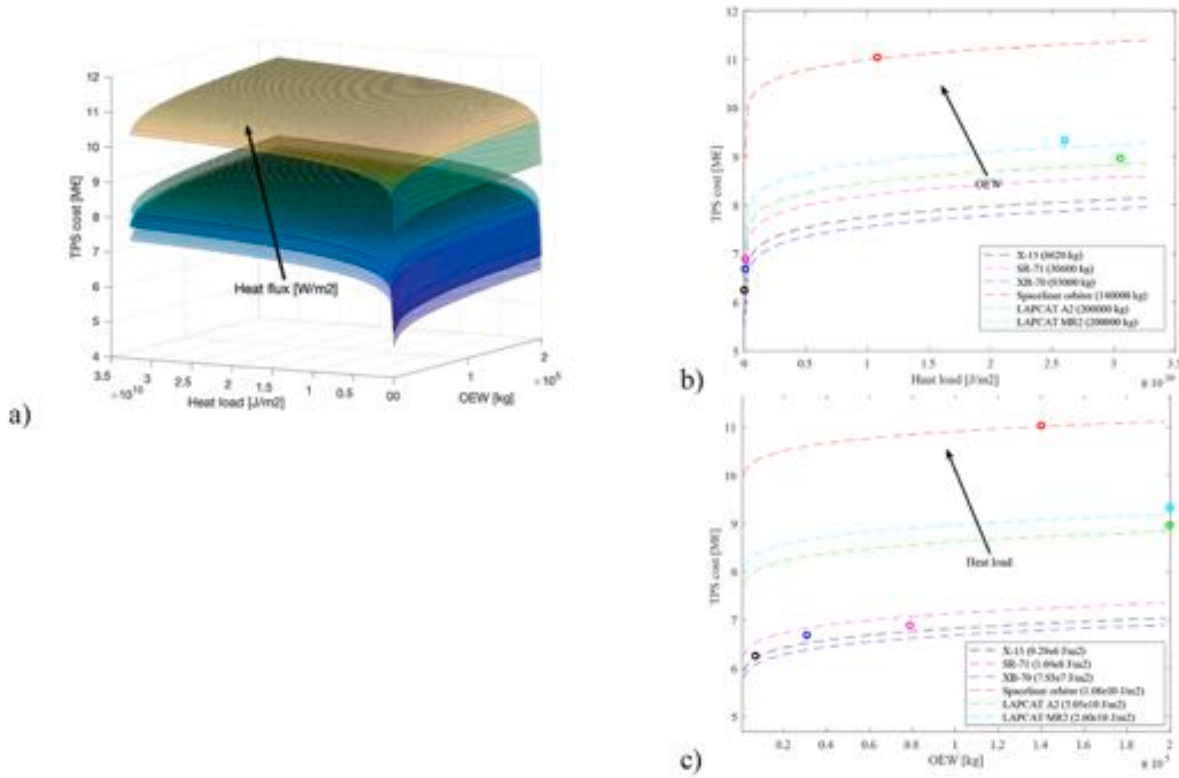

Fig. 13. a) 3D TPS PROD cost CER; b) TPS PROD cost as function of the heat loads and using the OEW as parameter; c) TPS PROD cost as function of the OEW and using heat load as parameter.

Table 2
Percentage breakdown of a hypersonic cruiser PROD costs.

Cost Items	Cost as percentage of Vehicle PROD	
Propellant subsystem	1,3%	Vehicle w/o engines PROD 78.0% of PROD
Thermal Protection Subsystem (TPS)	0,7%	
Thermal and Energy Management Subsystem (TEMS)	2,0%	
Integration	2,1%	
Structure	49,2%	
Landing Gear	0,8%	
Environmental Control Subsystem (ECS)	2,4%	
Ice Protection Subsystem (IPS)	0,7%	
Fire Protection Subsystem (FPS)	0,2%	
Flight Control Subsystem (FCS)	2,2%	
Avionic Subsystem	0,8%	
Electrical Power Subsystem (EPS)	16,8%	
Water Subsystem	0,1%	
Oxygen Subsystem	0,6%	
Lights Subsystem	0,1%	
Furnishing	<0,1%	
Low-Speed Engine	21,0%	Engines PROD 22.0% of PROD
High-Speed Engine	1,0%	

(purple, blue and green dots), representing some turbojet engines having similar thrusts are reported. Looking at all these points it is possible to see that even if turbojets are more expensive (due to more complex turbomachinery and components), they follow a trend which seems to be similar to the one depicted for high-speed engines.

2.3.1.4. Combined-cycle engine PROD CER. Complementary, Eq. (14) has been developed to support the production cost estimation of combined-cycle engines, where the same unit can operate in different speed regimes. The formulation is a combination of the low-speed and high-speed equations reported in Eq. (12) and Eq. (13).

$$F_{CCE} = C_{complexity}(k_{TJ}F_{ET} + k_{RJ}F_{ER})n_i^{\frac{\ln p}{\ln 2}} \tag{14}$$

Where F_{CCE} is the production cost of a combined-cycle engine in [WYr]; 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; $C_{complexity}$ is a multiplication factor used to compare the considered design to a an existing one (i.e. it can be exploited as escalation or reduction cost factor depending on the global configuration of the considered engine).

2.3.2. Subsystems level

The same process applied to RDTE costs has been replicated for subsystems production cost estimation.

2.3.2.1. Propellant subsystem PROD CER. The CER for propellant system production is not available in literature. Therefore, thanks to the availability of a set of cost data for high-speed vehicles built using PRICE-H Model and following the generic CER formulation suggested in TRANSCOST, the parametric formulation reported in Eq. (15) is defined. For this subsystem, two main drivers are considered: the vehicle operative empty weight and the engine dry mass. Please notice that Eq. (15), differently from the propellant subsystem RDTE CER, can be applied with different fuels and propellant since the effect of the kind of fluid, at preliminary stage, does not consistently affect the result (Fig. 12).

$$S_{prop_{prod}} = \left(0.48M_{OEW}^{0.38} + 0.5M_{E_{dry}}^{0.39}\right)n_i^{\frac{\ln p}{\ln 2}} \tag{15}$$

where $S_{prop_{prod}}$ is the production cost of a generic propellant subsystem; [WYr]; $M_{E_{dry}}$ is the sum of the engines' dry masses [kg] (e.g. 1 ATR+ 1 DMR); M_{OEW} is the Operative Empty Weight [kg].

2.3.2.2. Thermal protection subsystem PROD CER. Similarly, a specific

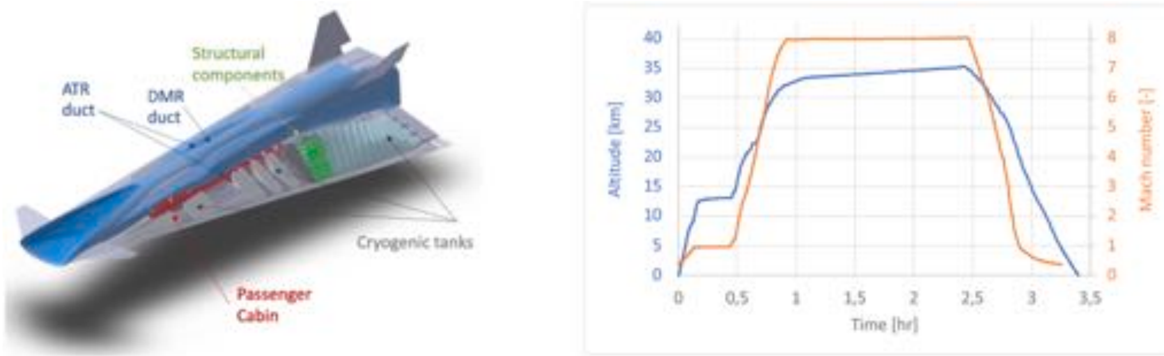

Fig. 14. STRATOFLY MR3 rendering (left) and mission profile with light altitude (blue) and Mach number (orange) versus mission time [36]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
RDTE Cost Estimation Input data @ Vehicle Level.

Input Drivers	Value for STRATOFLY MR3
Aircraft Operative Empty Mass M_{TOEW} (M_{OEW})	200 t (200,000 kg)
Single Turbojet engine dry mass: $(M_{dry})_{TJ}$	4000 kg
Single Ramjet Thrust: T_{RJ}	500 kN
Maximum TJ engine speed: v	1470 m/s @ 12 km
Maximum aircraft cruise speed: v_{cr}	8700 km/h @ 32 km
Mach Number: $\mathscr{M}$	8
Input Parameters	
Systems engineering/integration factor f_0	1.04
Learning curve factor: p	0.85
Region productivity factor: f_8	0.86

CER for Thermal Protection Subsystem for high-speed vehicles is not available. The CER here presented in Eq. (16) uses three cost drivers since it also includes the global integrated heat load Q, representing the accumulated heat during the entire mission, computed by time-integrating the flux across all of the aeroshell panels, as specified also by Refs. [34,35], together with heat flux q and OEW already introduced within development cost CER equation (Fig. 13). This is because, even if the heat flux is the main parameter used to select the type of material (and also of TPS), having a high effect on production cost, the heat load can be used to specify the amount of material (thickness) to be manufactured, with subsequent contribution to the final cost. For consistency, the same considerations reported in Section 2.2.2.3 for the reference heat flux have been made to develop the TPS production CER.

$$S_{TPS\,prod} = \left(0.5M_{OEW}^{0.19} + 3.41q^{0.12} + 0.68Q^{0.11}\right)n_i^{\frac{\ln p}{\ln 2}} \tag{16}$$

2.3.2.3. Thermal and energy management subsystem. The evaluation of TEMS production cost is instead performed with the same cost drivers already adopted to compute development costs, as the CER reported in Eq. (17) reveals. Again, also in this case, the proposed CER is applicable only to TEMS concepts similar to Refs. [32,33]. Notably, the Operative Empty Weight, the power generated by TEMS and boil-off flow rate are used as main drivers.

$$S_{TEMS\,prod} = \left(5.41M_{OEW}^{0.23} + 0.79P^{0.15} + 0.52\dot{m}^{0.19}\right)n_i^{\frac{\ln p}{\ln 2}} \tag{17}$$

The contributions of the remaining on-board subsystems to total PROD costs are shown in Table 2. Overall, around 40% of production cost is allocated to Powerplant, Propellant Subsystem, TPS and TEMS, while the rest cover around 60% of the total.

Table 4
RDTE cost estimation results for STRATOFLY MR3 @ vehicle level.

RDTE Costs for the Reference Baseline	
ATR	5353 M€ FY2020
DMR	916 M€ FY2020
Vehicle (w/o engines)	22,371 M€ FY2020
STRATOFLY MR3 (TRL1 – TRL9) – overall RDTE costs	25,615 M€ FY2020
STRATOFLY MR3 (TRL4 – TRL9) – actual RDTE from 2020 onwards	25,308 M€ FY2020

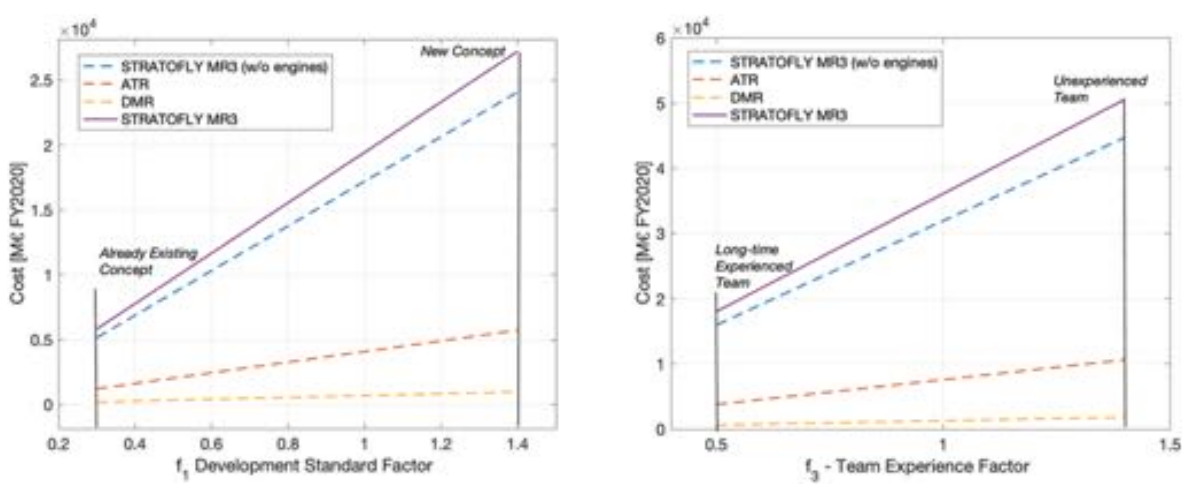

Fig. 15. RDTE Costs sensitivity to the Development Standard Factor (left) and to the Team Experience Factor (right).

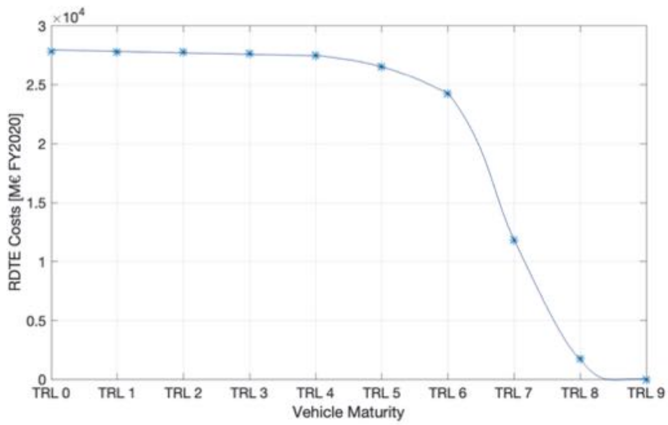

Fig. 16. RDTE Costs as function of Vehicle Maturity.

Table 5
PROD Cost Estimation Input data @ Vehicle Level.

Input Drivers	Value for STRATOFLY MR3
Aircraft Operative Empty Mass M_{TOEW} (M_{OEW})	200 t (200,000 kg)
Single Turbojet engine dry mass: $(M_{dry})_{TJ}$	4000 kg
Single Ramjet Thrust: T_{RJ}	500 kN
Maximum TJ engine speed: v	1470 m/s @ 12 km
Maximum aircraft cruise speed: v_{cr}	8700 km/h @ 32 km
Mach Number: $\mathscr{M}$	8
Input Parameters	
Systems engineering/integration factor f_0	1.04
Learning curve factor: p	0.85
Region productivity factor: f_8	0.86

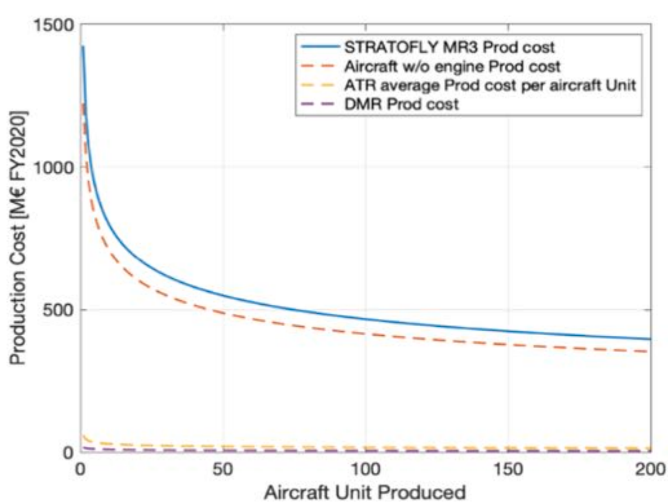

Fig. 17. Prod Costs as function of Aircraft Unit Produced (with a learning factor of 0.85).

For all other subsystems, PRICE-H Model, properly customized to cover high-speed vehicles, is used to define a percentage costs breakdown of the overall vehicle development cost. It is worth noticing that for sake of clarity, Table 2 contains all Subsystems, including those for which a specific parametric cost estimation is available.

3. The case-study: STRATOFLY MR3

Benefitting from the heritage of past European funded projects and, in particular LAPCAT II project, coordinated by ESA [29], the waverider configuration has been adopted and investigated in-depth throughout all flight phases for the hypersonic civil passenger aircraft, STRATOFLY MR3, which is a highly integrated system, where propulsion, aerothermodynamics, structures and on-board systems are strictly interrelated to one another, as highlighted in Fig. 14 [36]. STRATOFLY MR3 vehicle design is driven by its peculiar mission concept that can be summarized as follows: STRATOFLY MR3 is able to fly along long-haul antipodal routes reaching Mach 8 during the cruise phase at a stratospheric altitude (h > 30,000 m), carrying 300 passengers as payload. STRATOFLY MR3 has a waverider configuration to maximize

Table 6
PROD cost estimation results for STRATOFLY MR3 @ vehicle level.

TFU Production Costs for STRATOFLY MR3		
ATR (1st Unit)	75.43	M€ FY2020
ATR (2nd Unit)	64.11	M€ FY2020
ATR (3rd Unit)	58.30	M€ FY2020
ATR (4th Unit)	54.50	M€ FY2020
ATR (5th Unit)	51.72	M€ FY2020
ATR (6th Unit)	49.55	M€ FY2020
DMR	16.57	M€ FY2020
Vehicle (w/o engines)	1308	M€ FY2020
STRATOFLY MR3 – TFU	1678	M€ FY2020

Table 7
RDTE&PROD Cost Estimation Input data @ Subsystem Level.

Input Drivers	Value for STRATOFLY MR3
Aircraft Operative Empty Mass: M_{OEW}	200,000 kg
Liquid Hydrogen Density: ρ_F	70.8 kg/m^3
Single ATR engine dry mass: $(M_E)_{dry_{ATR}}$	4000 kg
Single DMR engine dry mass: $(M_E)_{dry_{DMR}}$	1400 kg
Power Generated by TEMS (P)	$15\ 10^6\ W$
Maximum Heat Flux (q)	$10^6 W/m^2$
Overall heat load accumulated during the mission (Q)	$3.05\ 10^{10} J/m^2$
Hydrogen Mass flow rate ($\dot{m}_{H2}$)	8 kg/s
Input Parameters	
Development standard factor: f_1	1.1 for Fuel Subsystem 1.2 for TPS 1.4 for TEMS
Team experience factor: f_3	0.8

Table 8
RDTE & PROD cost estimation results @ subsystem level.

Cost Items	RDTE Cost Estimation [M€ FY2020]	PROD (TFU) Cost Estimation [M€ FY2020]
Propellant Subsys	113.77	21.37
Thermal Protection Subsys	791.78	10.92
Thermal and Energy Management Subsys.	49.48	33.39
Integration	5097.00	36.01
Structure	13,471.00	825.82
Landing Gear	111.36	7.45
Environmental Control Subsystem (ECS)	449.73	23.59
Ice Protection Subsystem (IPS)	149.91	4.10
Fire Protection Subsystem (FPS)	160.62	3.73
Flight Control Subsystem (FCS)	621.06	37.26
Avionic Subsystem	209.87	13.66
Electrical Power Subsystem (EPS)	749.55	283.14
Water Subsystem	128.49	1.99
Oxygen Subsystem	128.49	2.48
Lights Subsystem	64.24	1.86
Furnishing	74.95	0.75
STRATOFLY MR3 Cost (w/o engines)	**22,371**	**1308**

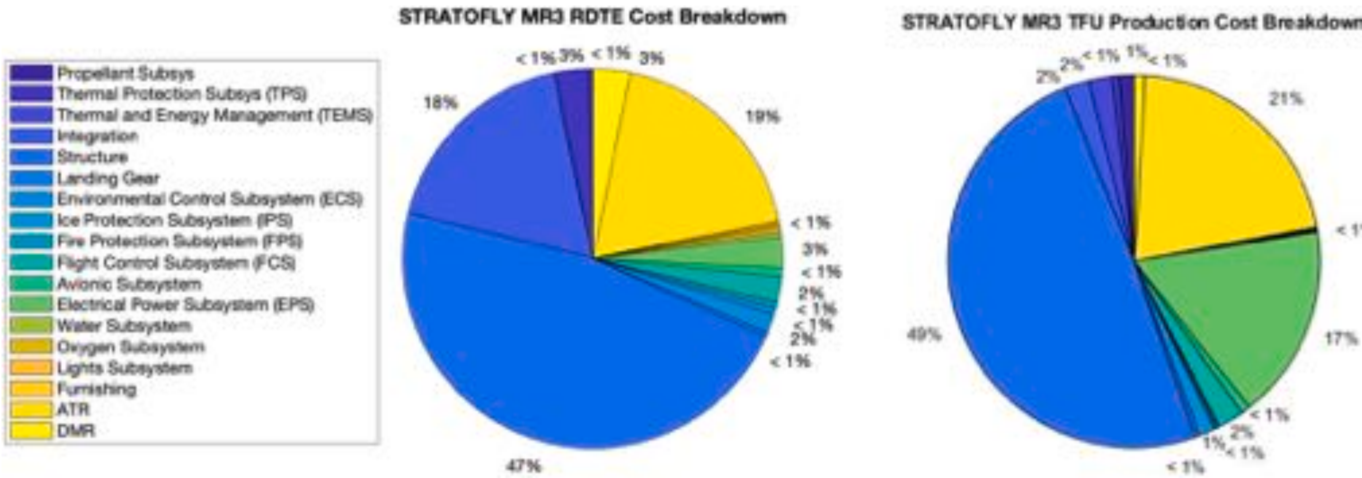

Fig. 18. RDTE (left) and PROD (right) Costs breakdown at subsystem level.

aerodynamic efficiency and improve range performance. Unlike many waverider concepts, STRATOFLY MR3 has the engines and related air ducts embedded into the airframe and located at the top of the vehicle to increase the available planform for lift generation without additional drag penalties, thus further improving the aerodynamic efficiency. In addition, this configuration allows optimizing the internal volume and guarantees to expand the jet to a large exit nozzle area without the need to perturb the external shape, which would lead to extra pressure drag. The mission profile is based on LAPCAT reference mission [29]. At the beginning of the mission, the Air Turbo Rocket, ATR, engines are turned on and the vehicle performs the first climb phase, which terminates at Mach = 0.95 at an altitude between 11 and 13 km. ATR is a turbine-based combined cycle engine, which brings together elements of the turbojet and rocket motors and provides the vehicle with a unique set of performance. This engine has in fact a high thrust-to-weight ratio and specific thrust over a wide range of speed and altitude, thus representing an excellent choice as accelerator engine up to high supersonic speeds. Then the vehicle performs the subsonic cruise to prevent sonic boom while flying over land. After the subsonic cruise, the supersonic climb starts, and the vehicle accelerates up to Mach 4. At the end of this phase, the ATR engines are turned off and the Dual Mode Ramjet (DMR) is activated to accelerate up to Mach 8, during hypersonic climb. DMR is the high-speed engine that can operate in both ramjet and scramjet modes of operations. The next phase, immediately after the hypersonic climb, is the hypersonic cruise at an altitude between 30 and 35 km. Eventually, the engines are turned off and the vehicle performs the descent towards the landing site.

3.1. Development and production cost estimation of STRATOFLY MR3

The cost model disclosed in the previous section has been applied to STRATOFLY MR3 vehicle and the results are reported and discussed hereafter.

3.1.1. RDTE @ vehicle level

As far as the RDTE Costs are concerned, Table 3 collects all necessary inputs to complete the estimation together with the values adopted for STRATOFLY MR3. Special attention must be paid to the tuning of the input parameters. According to the definition of the factors reported in[4], the absence of subcontracting emerges from the assumption of f_7 equal to 1, while the consideration of a nominal scenario, with no deviations from optimal schedule, brings to f_6 equal to 1. Complementary, considering that all the activities have been performed in Europe, the region productivity factor f_8 is set equal to 0.86. In parallel, a sensitivity analysis has been performed to assess the impact of the development standard factor and the team experience factor onto the final RDTE cost, as shown in Fig. 15. For STRATOFLY MR3, according to the definitions of the factors as reported in[4], f_1 is set to 1.3, reckoning that this case study can be considered a new concept involving new techniques and technologies, while f_3 is set to 0.7 in view of the fact that the team has already worked together in similar projects before.

Table 4 reports the results of the RDTE costs for STRATOFLY MR3, considering that the current average readiness level of the most significant technologies has been estimated equal to TRL4 in 2020 [37]. The expected reduction of STRATOFLY MR3 RDTE costs thanks to technology maturation is reported in Fig. 16.

3.1.2. PROD @ vehicle level

Similarly, STRATOFLY MR3 production costs are estimated on the basis of Eq. (9) to Eq. (17). Table 5 collects all the inputs necessary to complete the estimation of the selected case study. In line with [6], the same learning factor (equal to 0.85) has been applied to all aircraft components. Fig. 17 shows the Aircraft and its main components (Airframe&Systems and Engines) Production Costs as a function of the number of aircraft produced. The yellow line in Fig. 17 reports the average cost of a single ATR (one out of the 6 to be installed) per each ith aircraft produced. Table 6 lists the detailed results of the PROD costs estimation for STRATOFLY MR3.

3.1.3. RDTE & PROD @ subsystem level

The RDTE CERs at subsystem level (Eq. (6) to Eq. (8)) contain the development standard factor, f_1, per each considered item. As reported in Table 7, different values have been used to represent the actual status of maturation for STRATOFLY MR3. Specifically, for the fuel subsystem, the value of 1.1 is used to indicate a new subsystem design (i.e. bubble structured integrated cryo-tanks) with some new technical and operational features (i.e. slushed hydrogen to be preserved throughout the mission). As far as the Thermal Protection is concerned, a value of 1.2 is used, considering that besides the new design, few technical and operational features have to be developed. Eventually, the TEMS is reckoned as first-generation system, a new concept involving new techniques and technologies, thus a value of 1.4 is here assumed.

Table 8 and Fig. 18 summarize RDTE and PROD cost breakdown at subsystem level for STRATOFLY MR3.

4. Conclusions

The new parametric formulations for research, development and production cost estimation for hypersonic civil aircraft, described in this paper, moves beyond the state-of-the-art methodologies available in literature from many different perspectives, as summarized hereafter.

1. It integrates vehicle design and operational parameters, in addition to the mass, as cost drivers for the prediction of the vehicle life-cycle cost, such as vehicle maximum speed, engines maximum operative speeds, the maximum heat fluxes, the type of propellant used, etc …
2. It suggests how to include prediction margins to account for the uncertainties on the data-driven correlations;
3. It provides a first estimate of the costs of every on-board subsystem, including combined cycle engines and multi-functional subsystems;
4. It increases the granularity of the analysis up to technology level, thus providing a valuable support to Technology Roadmapping activities;
5. It allows to estimate the development cost on the basis of the current technology readiness level;
6. It provides the results of a unique test case, namely the STRATOFLY MR3 waverider concept;
7. It provides unique capabilities for the integration of cost estimation since very early conceptual design stage [38].

Future works will be focused on the analysis of potential update of equations dedicated to different powerplant architectures, as well as on the characterization of costs associated to the airframe and related subsystems, for which a simple approach is suggested in this paper. Dedicated equations for the other subsystems are in fact expected. Also, a wider exploration of the impact of TRL on the development cost is required, with particular attention to those technologies that can have different values of readiness level, so to properly understand how the formulation of RDTE costs can adapt to different development starting points. The validation of the proposed model through the application of the set of CERs to different case studies is also planned.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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