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Upgrade of HyCost methodology and tool to support LCC estimation of reusable access to space vehicles

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Abstract

This paper aims at presenting the latest upgrades to HyCost Methodology and Tool, developed by Politecnico di Torino under funding and supervision of the European Space Agency (ESA), to support Life Cycle Cost (LCC) estimation of reusable access to space vehicles. The main idea is to support the designer in cost estimation activity during conceptual and preliminary design phases, allowing the evaluation of Research, Development, Test and Evaluation (RDTE) Costs, Production Costs, as well as Direct and Indirect Operating Costs (DOC and IOC), for a wide set of aerospace systems, from supersonic civil aircraft to hypersonic and, in general, high speed vehicles. Politecnico di Torino has already proposed a LCC methodology and tool called "HyCost 1.0" specifically tailored to air-breathing high-speed transportation systems. This paper discloses the upgrades of HyCost 1.0, i.e. "HyCost 2.0" methodology, to extend the methodology and tool capability to future Reusable Access to Space Vehicles. The main goal of this research activity is to evaluate the applicability of already existing parametric cost estimation relationships (CERs) to the peculiarities of Reusable Access to Space Vehicles and if necessary, to define new equations. Specifically, this new set of equations shall be able to capture the impact of different vehicle configurations (e.g. staging strategy, staging Mach number, parallel or series configuration, etc…) onto costs, as well as the impact of the most promising propulsive solutions, ranging from scramjet and combined cycle engines to rocket engines. Ultimately, this new methodology and implemented routines are applied and validated using the SpaceX Starship case study.

Keywords: *Life-Cycle Costs Estimation, Cost Estimation Relationships, Reusable Access to Space Vehicles.*

1. Introduction

In the last decades, the integration of costs analysis into conceptual design activities has proven to be crucial to address the multifaceted features of innovative systems: this capability seems now essential to assess the viability of reusable launchers in the near-term future. In a current worldwide scenario characterized by huge launch costs, reusable access to space systems could represent the only economically sustainable option to manage the continuously growing launch demand. Since the Sixties, several reusable concepts have been analyzed, culminating into the development of the most complex and technological advanced partially reusable launcher ever built, the Space Shuttle or Space Transportation System (STS). As it is well known, the great technological complexity of Space Shuttle STS highly impacted onto its reliability and, as a consequence, led to an unexpected increase of

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refurbishment effort, as well as of the overall launch cost. Nowadays, thanks to the continuous technological progresses and new commercial perspectives, a substantial launch costs decrease has been attained by Space Exploration Technologies (SpaceX) for partially reusable systems such as the Falcon 9 and the Falcon Heavy rockets [1]. Benefitting from the Falcon 9, Falcon Heavy, and Dragon experiences, the US company is currently developing and testing Starship, a new concept of fully reusable space transportation system, promising crew and cargo delivery to Earth orbit, to the Moon, up to Mars and beyond [2–4]. Another noteworthy example of Two Stage to Orbit (TSTO) rocket vehicle with fully reusable first stage is the New Glenn [5-6] by Blue Origin. Such large-scale Reusable Launch Vehicle (RLV) commercial programmes are still at a conceptual stage in the European framework. However, it is worth mentioning the SKYLON Single Stage to Orbit (SSTO) spaceplane [7,8] under design by Reaction Engines in UK. SKYLON is equipped with the Synergetic Air-Breathing Rocket Engine (SABRE) [7,8], an innovative hydrogen-fueled combined cycle engine characterized by airbreathing mode up to Mach 5 and transitioning to pure rocket mode up to orbital velocity. Current development and test activities focus on the engine core, with recent completion of testing for the advanced hydrogen pre-burner and the heat exchanger connected to it [9,10].

These studies and projects represent only the most recent and eminent research activities currently on going in the complex framework of future RLVs. As mentioned, several analyses and tests have already been performed mainly in the US and with commercial purposes. However, the path towards a fully reusable access to space vehicle is still hampered by some technological developments as well as by the uncertainties of their economic success. Therefore, the integration of a Life Cycle Cost (LCC) algorithm at conceptual design stage could play a fundamental role in guiding engineers towards the selection of the most economically sustainable concepts. This could prevent from huge resource wasting as experienced in the past and from the risk of budget overrun due to funding of impractical technological solutions.

In view of this challenging scenario, this paper describes an innovative methodology for LCC assessment of future RLVs applicable since early design stages. In this context, Politecnico di Torino (PoliTo) in collaboration with the Europan Space Agency (ESA) already proposed a LCC methodology and tool called "HyCost" [11] (here referred to as "HyCost 1.0") specifically tailored for high-speed air-breathing (AB) transportation systems, including supersonic and hypersonic civil aircraft, conceived for point-to-point transportation. This paper discloses the enhancements of HyCost 1.0, i.e. "HyCost 2.0" methodology, to extend methodology and tool capabilities to Reusable Access to Space Vehicles. The main novelty of the proposed approach is that, basing on the heritage from previous LCC estimation activities, the updated methodology provides a complete integrated framework for both high-speed transportation systems and RLVs LCC estimation, covering a wide spectrum of concepts and design solutions.

As depicted in Fig 1, the new approach is based on the classical costs subdivision proposed in TransCost [12], i.e. Research, Development, Test and Evaluation (RDTE), Theoretical First Unit (TFU) Production Cost, as well as Ground and Flight Operations Cost. RDTE and TFU Production costs are split between Airframe (i.e. structures and on-board systems excluding engines) and Engines components, while Ground and Flight Operations Cost are made up by Direct Operating Cost (DOC), Refurbishment and Spares Cost (RSC), together with Indirect Operating Cost (IOC), basing on the definitions provided in [12,13]. Each cost item is evaluated with specific Cost Estimation Relationships (CERs), which can be either generic equations, whose validity extends from high-speed aircraft to Reusable Access to Space, or specific equations tailored for a well-defined and restricted application.

As summarized in Fig 1, the new HyCost 2.0 methodology combines newly derived CERs with state-of-the-art (SoA) equations, already available in literature, to provide a comprehensive approach to LCC assessment. In particular, after a brief description of the main gaps of SoA approaches in relation to RLVs LCC assessment, a concise description of novelties contained in HyCost 2.0 is reported, together with some software implementation details. Ultimately, the paper discuss the results of application of the new methodology and tool to SpaceX Starship vehicle and the comparison with commercial data.

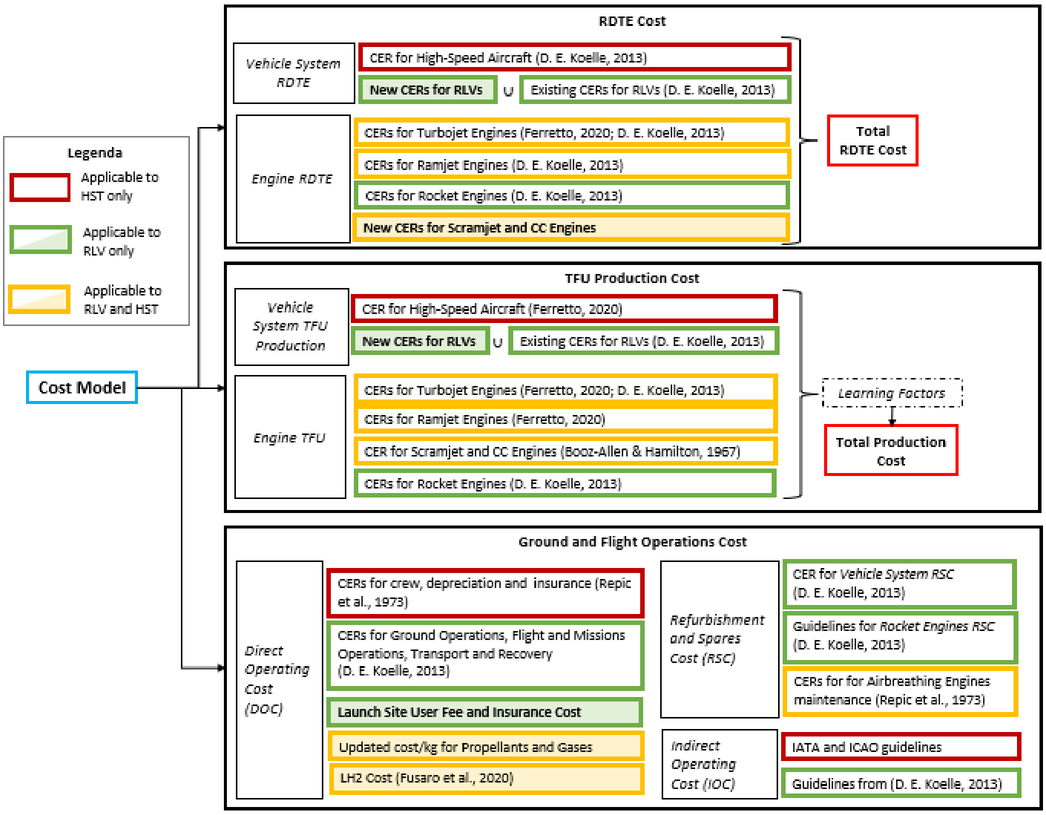


Fig 1. HyCost 2.0 Methodology Overview

2. Cost Estimation: State-of-the-art for Reusable Access To Space Systems

Cost estimation methodologies are based on the heritage from past projects: available cost data are collected and, thanks to dedicated regression techniques, parametric equations able to assess RDTE, Production, and Operating costs (i.e LCC) of a product [11] (i.e. CERs) are suggested. As far as RLVs are concerned, very few past projects are available, thus cost estimation process has to face a substantial lack of actual cost data, main basis of new LCC methodologies development. As a result, only few cost estimation methodologies are already available in literature to determine the economic viability of these concepts.

The first cost estimation methodology for future RLVs was proposed in [14] to cover a wide range of configurations, from airbreathing first stages to completely recoverable vertical take-off rockets. However, the mathematical formulation of this model was built upon cost data of prototypes and concepts (like Astro [15]) with technologies of the Sixties, thus preventing from a direct exploitation for up-to-date or future concepts and technologies [16][17]. Another remarkable approach was presented by Booz-Allen [18], specifically developed to support the preliminary assessment of TFU production cost of advanced airbreathing engines for future RLVs. In this formulation, main cost-drivers are maximum rated thrust, engine operational altitude, and normal rated thrust divided by dry engine weight. The CER is based on 57 observations, mainly military turbojets (e.g. J-58 engine installed on the SR-71 aircraft) and, according to [19], it might also be applicable to advanced airbreathing concepts such as ATRs (Air Turbo Rockets) and Scramjet engines. Even though the statistical population differs from main applications here envisaged, the suggested mathematical formulation appears a promising basis for development of the new models.

The last and, probably, the most comprehensive and widely used cost methodology is the TransCost approach [12] proposed by D.E. Koelle. TransCost, which has been already used as valuable literature source by the authors in the framework of [11], is mostly based on expendable launchers cost data but it also proposes CERs for a preliminary assessment of future RLVs, based on independent cost estimations from classified tools developed during several independent studies (e.g., FESTIP [20]). It means that CERs derivation may be based not only on real cost data but, lacking "real" costs, they might be built basing on cost estimation data coming from previous studies. However, a detailed analysis of available TransCost CERs clearly reveals that the level of detail (i.e. granularity level) of the proposed equations is not sufficient to assess the impact of peculiar RLV configurations onto costs as required in the present work. Moreover, a unique RDTE CER is suggested for Advanced Aircraft (such as Concorde), Airbreathing SSTO and Airbreathing First Stage of TSTO (even if underlying database does not effectively include Airbreathing First Stages), thus it is not possible to appreciate the impact of specific airbreathing vehicle types (e.g military aircraft vs. Airbreathing First Stage of TSTO) onto RDTE costs. Similar remarks apply to the CER for TFU Production of High-Speed Aircraft/Winged First Stage Vehicles in TransCost. For Vertical Take-off Horizontal Landing (VTHL) Fly-back boosters, Trivailo [21] already proposed an updated version of TransCost CER by revising cost data with internal documents available at Deutsches Zentrum für Luft- und Raumfahrt (DLR). For engines, TransCost provides useful CERs for RDTE cost of turbojet and ramjet engines, as well as for liquid and solid propellant rocket engines thanks to the huge availability of real cost data (specifically for turbojet and rocket engines). Concerning TFU production cost, turbojet and rocket engines are covered, while equations for ramjet and scramjet engines are not available due to lack of detailed production cost data. In an attempt to fill this gap, ramjet engine TFU production cost suggested in [11] by the authors can be exploited. In addition, specific relationships for other engine types of great interest for future RLVs, such as Combined Cycle (CC) engines, are missing in the last available version of TransCost [12] (i.e. "TransCost 2013"). However, a set of RDTE CERs for specific types of CC Engines, i.e. Rocket/Ramjet, Air Ejector/Ramjet/Scramjet/Rocket (i.e. 4 mode engine) and Turboramjet/Rocket, was proposed in a previous TransCost version [22] (i.e. "TransCost 1991"). These CERs, function of engine dry mass, are also reported in [19]. By comparing them with the RDTE CER for liquid propellant rocket engines provided in TransCost 1991, it can be noticed that all CERs have the same power exponent (i.e. 0.635) and the extent of costs associated to the different propulsive strategies depends merely on the multiplicative coefficient (i.e. 152, 200, 300 or 500) applied to the engine dry mass. Moreover, liquid propellant rocket engine RDTE CER from TransCost 1991 tends to overestimate costs with respect to the latest version of the same CER in TransCost 2013, which is based on more recent and technologically advanced rocket engines. As a result, CC Engines RDTE equations from TransCost 1991 might overestimate actual costs. However, the possibility to preliminary estimate CC Engines RDTE cost starting from liquid propellant rocket engines appears interesting and promising for future improvements. For completeness, it is worth mentioning that in [11], the authors already proposed a general formulation for RDTE and TFU Production cost of Turboramjet Combined Cycle Engine as a function of RDTE and TFU Production cost of turbojet and ramjet components constituting the engine.

Ultimately, accounting for Ground and Flight Operations Cost, TransCost [12] considers the contribution of DOC, RSC, and IOC as already discussed in relation to Fig 1. As far RSC is concerned, only rocket RLVs are modelled in detail. To broaden the spectrum to airbreathing engines, the NASA-modified ATA CERs [23] (also analyzed in [11]) can be exploited to assess maintenance effort related to advanced airbreathing engines on future RLVs.

3. Innovative HyCost 2.0 Methodology

3.1. Methodology Overview

As mentioned, the purpose of the present paper is to present a complete framework of LCC estimation for a wide range of RLV concepts. The literature analysis summarized in the previous Section highlights that available SoA approaches are not directly suitable to appreciate the impact of specific RLV configurations onto costs since early design activities. As a result of this analysis, Figure 1 summarizes the main structure of the new HyCost 2.0 methodology applicable to both case studies, i.e. high-speed transportation systems and future RLVs, highlighting cost items for which SoA methodologies are applicable and those for which new CERs are derived to meet desired granularity level.

In particular, as far as high-speed transportation systems are concerned, Airframe RDTE and TFU Production CERs from HyCost 1.0 [11] are included. Conversely, for RLVs, TransCost [12] CERs for the same items are often based on heterogeneous databases, so that the effect of specific RLV configurations onto costs is not highlighted. Therefore, as shown in Figure 1, a new set of CERs associated to well-defined RLV categories is proposed. For Turbojet/Ramjet/Rocket Engines RDTE and for Turbojet/Rocket Engines TFU Production cost, original TransCost CERs are suggested, underlying their applicability to the two case studies, while for Ramjet Engine TFU Production cost the equation from [11] is recommended. Concerning CC and Scramjet engines, they cannot be fully characterized in terms of RDTE cost with SoA approaches, so new CERs are provided, while Booz-Allen CER [18,19] is suggested for TFU Produciton cost. As far as Ground and Flight Operations Cost is concerned, the DOC model reported in TransCost is exploited for RLVs, while NASA-modified ATA CERs [11,23] are proposed for high-speed transportation systems. For both categories, updated figures for Propellant and Gases cost per kg can be found in [24,25]. For RSC, TransCost model for rocket vehicles and engines is adopted for rocket RLVs and extended with NASA-modified ATA CERs to assess maintenance cost of advanced air-breathing engines for high-speed transportation systems and RLVs. Eventually, lacking more detailed models for IOC, guidelines from HyCost 1.0 [11] and TransCost are adopted, respectively, for high-speed transportation systems and RLVs.

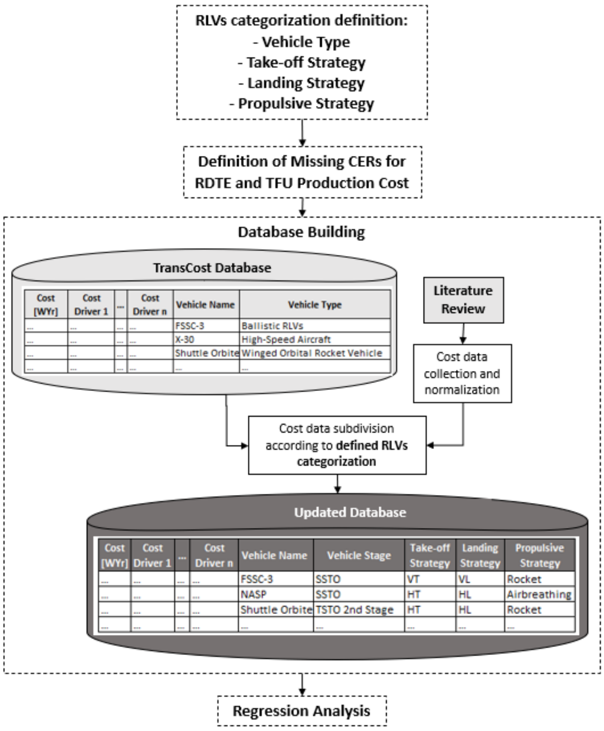
3.2. New CERs for RLVs Airframe RDTE and TFU Production Cost

As shown in the activity flow of Fig 2, the first step towards the derivation of new equations for Airframe RDTE and TFU Production Cost is the definition of a proper RLVs categorization. This allows to settle all the main RLV categories to be handled by the new model considering design characteristics expected to have a major impact onto costs. In particular, the following features are identified: 1) Vehicle Type/Stage (e.g. SSTO, First Stage of TSTO or Second Stage of TSTO), 2) Take-Off Strategy (TO), i.e. Horizontal or Vertical, 3) Landing Strategy (LND), i.e. Horizontal, Vertical or Splashdown and 4) Propulsive Strategy (Prop.), i.e. Airbreathing (AB) or Rocket (R). Exploiting this RLV categorization, the second step highlighted in Fig 2 consists in defining RDTE and TFU Production CERs not available from SoA and thus to be derived in the present research. It is worth highlighting that the precise distinction between RLV categories would ease CERs exploitation, avoiding any misuse in their application as experienced for original TransCost methodology. As a result, the following list of missing Airframe RDTE and TFU Production CERs is identified:

- HTHL Rocket TSTO 1st Stage RDTE CER;
- Rocket TSTO 2nd Stage RDTE CER;
- HTHL Rocket SSTO RDTE CER;
- VTHL Rocket SSTO RDTE CER;
- HTHL Aibreathing TSTO 1st Stage RDTE CER;
- VTVL Rocket TSTO 1st Stage RDTE CER.
- HTHL Rocket TSTO 1st Stage TFU Production CER;
- Rocket TSTO 2nd Stage TFU Production CER;
- HTHL Rocket SSTO TFU Production CER;
- VTHL Rocket SSTO TFU Production CER;
- HTHL Aibreathing TSTO 1st Stage TFU Production CER;
- VTHL Rocket TSTO 1st Stage TFU Production CER;
- VTVL Rocket TSTO 1st Stage TFU Production CER.

It is highlighted that RDTE CER for VTHL Rocket First Stage of TSTO (also referred as Fly-back booster) is not included since the equation derived by Trivailo [20] can be adopted. Moreover, for Vertical Take-off Vertical Landing (VTVL) Rocket SSTO, RDTE and TFU Production CERs for Ballistic RLVs suggested by TransCost are judged suitable considering the significant number of concepts included in the underlying database, while RDTE and TFU Production CERs for Horizontal Take-off Horizontal Landing (HTHL) Airbreathing SSTO are not listed because these concepts are considered technically unfeasible with current technologies. Please, note that the focus on SSTO and TSTO is justified by the current research and commercial interest for these specific RLV types. Furthermore, for VTVL Rocket TSTO First Stages, TransCost CERs for both RDTE and TFU Production, originally based on expendable stages and deemed applicable to RLVs as well, are enriched with cost estimation data specifically related to reusable stages (i.e. Falcon 9 from TrasCost itself and HyperNova [24]).

Newly developed RDTE CERs and TFU Production CERs are reported in the following Tables.



Cost [WYr]	Cost Driver 1	...	Cost Driver n	Vehicle Name	Vehicle Type
...	...	...	...	FSSC-3	Ballistic RLVs
...	...	...	...	X-30	High-Speed Aircraft
...	...	...	...	Shuttle Orbite	Winged Orbital Rocket Vehicle
...	...	...	...	...	...

Cost [WYr]	Cost Driver 1	...	Cost Driver n	Vehicle Name	Vehicle Stage	Take-off Strategy	Landing Strategy	Propulsive Strategy
...	...	...	...	FSSC-3	SSTO	VT	VL	Rocket
...	...	...	...	NASP	SSTO	HT	HL	Airbreathing
...	...	...	...	Shuttle Orbite	TSTO 2nd Stage	HT	HL	Rocket
...	...	...	...	...	...	...	...	...

Fig 2. Activities' Flowchart for new Airframe RDTE and TFU Production CERs derivation

Table 1. Newly developed CERs to estimate RDTE cost of RLVs

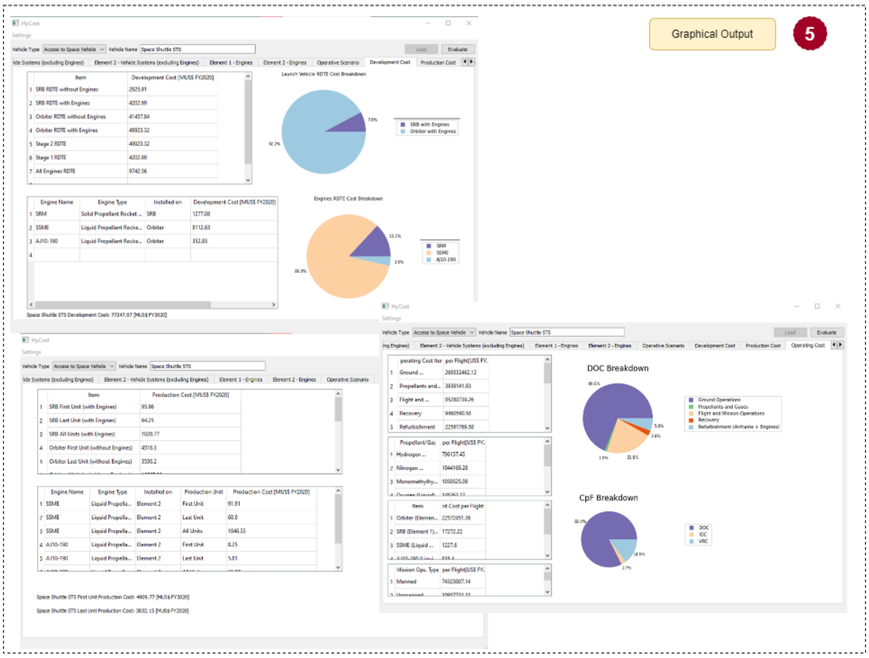
Cost Item	**New RDTE CERs**
HTHL Rocket First Stage RDTE	$176.51W_{dry(w/o\ eng)}^{0.49}$
HTHL Airbreathing First Stage and Advanced Aircraft RDTE	$22857 + 0.24W_{dry(w/\ eng)}$
HTHL Airbreathing First Stage RDTE	$0.68 + 922.56W_{dry(w/\ eng)}^{0.12}Mach^{1.39}$
RDTE CER for Liquid Propellant Rocket 2° Stage with HL (1)	$21470 + 0.69W_{dry(w/out\ eng)}$
Rocket Second Stage with HL RDTE (2)	$32.82W_{dry(w/\ eng)}^{0.68}Mach^{0.064}$
VTHL or HTHL Rocket SSTO RDTE	$1.71W_{dry(w/out\ eng)}^{0.96}$
VTVL Rocket SSTO RDTE	$743.36W_{dry(w/out\ eng)}^{0.39}$
VTVL Liquid Propellant Rocket First Stage RDTE	$96.42W_{dry(w/out\ eng)}^{0.56}$
Scramjet Engine RDTE	$1.5982 \cdot M_{E_{dry}} + 10391$
Rocket/Ramjet CC Engine RDTE	$546.71M_{E_{dry}}^{0.48}$
Turboramjet/Rocket CC Engine RDTE	$364.47M_{E_{dry}}^{0.48}$
Air Ejector/Ramjet/Scramjet/Rocket CC Engine RDTE	$911.18M_{E_{dry}}^{0.48}$

Table 2. Newly developed CERs to estimate TFU Production costs of RLVs

Cost Item	**New TFU Production CERs**
HTHL Liquid Propellant Rocket First Stage TFU Production	$2607.7+0.017W_{dry(w/o\ eng)}$
VTHL First Stage TFU Production	$420.56+0.02W_{dry(w/o\ eng)}$
HTHL Airbreathing First Stage TFU Production	$1.55W_{dry(w/\ eng)}^{0.54}Mach^{0.67}$
VTVL, VTHL and HTHL Rocket SSTO TFU Production	$0.0495W_{dry(w/out\ eng)}^{1.027}$
Liquid Propellant Rocket Second Stage with HL TFU Production	$0.212W_{dry(w/out\ eng)}^{0.978}$
VTVL Liquid Propellant Rocket First Stage TFU Production	$1.786W_{dry(w/out\ eng)}^{0.584}$

4. HyCost 2.0 Software Implementation

The cost model described above has been implemented within the open-source Python Qt environment by means of a Graphical User Interface (GUI). The resulting tool (called HyCost) aims at supporting engineers in performing LCC estimation during the conceptual and preliminary design phases. HyCost is based on a tab-oriented architecture, i.e. it consists of several "tabs" or sections enclosed in the same window. Thanks to this well-structured architecture, the tool is compact, straightforward, flexible and user-friendly. The tab-oriented tool also provides high modularity since it is possible, at any time, to insert a new tab to provide an additional feature. For example, dealing with RLVs, a noteworthy feature of the tool is the possibility to define a vehicle in terms of "Number of Vehicle Elements type" and "Number of Stages". The former allows to preliminary specify the overall vehicle configuration, defining the number of different type of elements constituting the vehicle. Complementary, the input "Number of Stages" allows to define the number of "groups" in which the specific element types are gathered. Please, notice that this feature has been introduced within the tool to model complex RLV systems like the Space Shuttle as well as more conventional SSTO and TSTO designs. This distinction is fundamental for the tool to determine, for example, the exact number of units (for each element type) to be produced. However, in case of SSTO and TSTO vehicles, the definition of elements and stages is more straightforward since they are constituted by one (or two) elements coinciding with the stages. Thanks to this preliminary description, it is possible to appreciate the great flexibility of the tool in terms of vehicle configuration definition. Moreover, HyCost allows to define the engine types installed on each vehicle element with related characteristics (entailing both airbreathing and rocket engines) as well as all the inputs required by the operating cost model to define the operative scenario of the RLV. In the end, after running the tool with the inputs specified in the previous tabs, additional tabs are generated to show the final outputs of the cost estimation. Along with summary tables with RDTE, Production, DOC and IOC, a graphical summary of the main outputs is also provided.



	Item	Development Cost [MUS$ FY2020]
1	SRB RDTE without Engines	2925.91
2	SRB RDTE with Engines	4202.99
3	Orbiter RDTE without Engines	41457.84
4	Orbiter RDTE with Engines	49923.32
5	Stage 2 RDTE	49923.32
6	Stage 1 RDTE	4202.99
7	All Engines RDTE	9742.56

	Engine Name	Engine Type	Installed on	Development Cost [MUS$ FY2020]
1	SRM	Solid Propellant Rocket ...	SRB	1277.08
2	SSME	Liquid Propellant Rocke...	Orbiter	8112.63
3	AJ10-190	Liquid Propellant Rocke...	Orbiter	352.85
4				

Space Shuttle STS Development Cost: 77247.97 [MUS$ FY2020]

	Item	Production Cost [MUS$ FY2020]
1	SRB First Unit (with Engines)	95.96
2	SRB Last Unit (with Engines)	64.25
3	SRB All Units (with Engines)	1028.77
4	Orbiter First Unit (without Engines)	4516.3
5	Orbiter Last Unit (without Engines)	3536.2

	Engine Name	Engine Type	Installed on	Production Unit	Production Cost [MUS$ FY2020]
1	SSME	Liquid Propella...	Element 2	First Unit	91.91
2	SSME	Liquid Propella...	Element 2	Last Unit	60.9
3	SSME	Liquid Propella...	Element 2	All Units	1046.33
4	AJ10-190	Liquid Propella...	Element 2	First Unit	8.25
5	AJ10-190	Liquid Propella...	Element 2	Last Unit	5.81

Space Shuttle STS First Unit Production Cost: 4909.77 [MUS$ FY2020]

Space Shuttle STS Last Unit Production Cost: 3832.15 [MUS$ FY2020]

	perating Cost Iter	per Flight[US$ FY.
1	Ground ...	269332462.12
2	Propellants and...	3939141.93
3	Flight and ...	85280739.26
4	Recovery	9460590.50
5	Refurbishment	22591789.58

	Propellant/Gas	per Flight[US$ FY.
1	Hydrogen ...	796157.45
2	Nitrogen ...	1944169.28
3	Monomethylhy...	1050525.09

	Item	nt Cost per Flight
1	Orbiter (Elemen...	22572451.36
2	SRB (Element 1)...	17272.22
3	SSME (Liquid ...	1227.6

	Mission Ops. Type	per Flight[US$ FY.
1	Manned	74323007.14

Fig 3. HyCost Tool Outputs Tabs

5. Application to SpaceX Starship TSTO

SpaceX is developing a fully reusable TSTO concept generically referred to as Starship. However, more precisely, Starship is the second stage of the TSTO (also referred to as "spacecraft"), while the first stage (or booster) is the Super Heavy rocket. Conceived with the aim to deliver payload in LEO (to perform mission to Moon, Mars (and beyond) as well as for intercontinental passenger transport (as Hypersonic Space Transportation System), "Starship is designed to evolve rapidly to meet near term and future customer needs while maintaining the highest level of reliability" [25]. Both crew and uncrewed Starship versions are under development (see Fig. 4). However, it is worth highlighting that the crew configuration is specifically targeting the ambitious SpaceX goal of "making life multiplanetary", transporting up to 100 people from Earth into LEO and on to the Moon and Mars [3] [25] For the sake of validation, the uncrewed version of the Starship is considered hereafter. Despite great part of design information available for the Starship refer to the Mars mission [2], [3], [4], data related to the LEO scenario can be extrapolated.


(a) (b)

Fig 4. (a) Artist's impression of satellite payload release from Starship payload bay in LEO [2] ; (b) Starship crew (left) and uncrewed (right) configurations [25]

As far as payload capability is concerned, SpaceX claims that Starship can deliver over 100 tons to LEO. Nevertheless, recent independent simulation studies at DLR [26] using data available in literature [3][4] revealed that, more realistically, 40 tons can be effectively delivered to LEO assuming a safe return to launch site scenario. Despite this estimation is far below Space X projections, a 40-tons payload capability is still highly competitive compared to the most promising payload options discussed in old studies available in literature. Both the Starship and the Super Heavy are equipped with a number of rocket engine modules, called Raptor, currently under development at SpaceX. Raptor is a full-flow LOX/CH_4 fueled rocket engine "*and is going to be the highest chamber pressure engine of any kind ever built*" [3]. Considering that the design of the SpaceX Starship TSTO is still on-going, the Starship and Super Heavy Booster characteristics are constantly under modification. However, to validate the newly developed CERs, the design features mentioned in [3] are mostly taken as reference (except for the Super Heavy Propellant mass, for which the lower value provided in [27] is used). For sake of clarity, Table 3 collects the main design features of interest for this work. As far as Raptor Engine dry mass is concerned, its value is not reported in literature, and a preliminary estimation has been performed, exploiting sizing relationships provided in [28] for kero-LOx and storable engines. This allows to derive a dry mass of 2448 kg. The final value of Raptor engine dry mass reported in Table 3 is obtained by assuming 30% mass reduction thanks to 3D printing manufacturing [17].

Cycle	Full-flow staged combustion
Oxidizer	Subcooled liquid oxygen
Fuel	Subcooled liquid methane
Chamber Pressure	300 bar
Throttle Capability	20% to 100% thrust

Sea-Level Nozzle
Expansion Ratio: 40
Thrust (SL): 3,050 kN
Isp (SL): 334 s

Vacuum Nozzle
Expansion Ratio: 200
Thrust: 3,500 kN
Isp: 382 s

Fig 5. Key characteristics of the Raptor engine [2]

Table 3. SpaceX Starship TSTO design characteristics from [2]

	Starship	**Super Heavy**
Number of Raptor Engines	9	42
Dry Mass (with engines) [ton]	150	275
Dry Mass (without engines) [kg]	134,579.1	203,035.79
Propellant Mass [ton]	1950	3400
Residuals [ton]	204 (6% of Propellant Mass)	Not required
Net Mass (without engines) [kg] (Dry Mass without engines plus residuals)	407,035.79	Not required
Raptor Engine Dry Mass [kg]	1713.43	
Launch Mass [ton]	5815 (with 40 ton of payload to LEO)	

Following the RLVs classification discussed in previous section, the Super Heavy is modelled as a fully reusable VTVL first stage rocket vehicle, while Starship is a fully reusable rocket second stage with HL.

5.1. Space X Starship TSTO Development Costs

The indications reported in Figure 1 together with the new set of equations summarized in Table 1 are used to assess RDTE cost of the SpaceX Starship TSTO.

Table 4 collects the results obtained for the selected case study. For sake of clarity, both governmental and commercial scenarios are reported for all vehicle systems and engines under consideration. Despite the SpaceX Starship TSTO is a purely commercial concept, such complete analysis allows to appreciate the great cost difference in case of governmental funding, in line with the observations reported in [12].

Table 4. RDTE cost results for SpaceX Starship TSTO

Element	**Governmental Scenario B€ [FY 2021]**	**Commercial Scenario B€ [FY 2021]**
Super Heavy	19.40	6.55
Starship	49.34	16.65
Raptor	1.77	0.60
Total	**76.27**	**25.74**

5.2. Space X Starship TSTO Production Costs

Similarly, the indications reported in Figure 1 together with the new set of equations summarized in Table 2 are used to assess the TFU cost of the SpaceX Starship TSTO.

Table 5. TFU Production cost results for SpaceX Starship TSTO

Element	**Governmental Scenario M€ [FY 2021]**	**Commercial Scenario M€ [FY 2021]**
Super Heavy	18.36	302.29
Starship	8494.18	2972.96
Raptor	24.89	9.03
First Stage (First Unit)	1370.55	479.69
Second Stage (First Unit)	8573.78	3000.82
TSTO Vehicle (First Unit)	**10,549.94**	**3692.48**

Once the TFU estimation is available, the analysis of Production Costs should be completed with an estimation of Total and Average Production Costs, knowing the total number of units to be produced in a specified timeframe or estimating it on the bases of the foreseen market demand.

Specifically, according to [2], "*the threshold for a self-sustaining city on Mars or a civilization would be a million people. If you can only go every 2 years and if you have 100 people per ship, that is 10,000 trips. […] However, 10,000 flights is a lot of flights, so ultimately you would really want in the order of 1,000 ships.*" [2]). More precisely, considering 12 reuses for each Starship, 834 second stage vehicles are required. Moreover, assuming a lifetime of 1000 launches for each Super Heavy and, per each Mars mission, 6 launches (to allow the refill), a total number of 60,000 Super Heavy launches are envisaged during the whole SpaceX Starship TSTO program to Mars. This means that at least 60 Super Heavy Boosters are needed (surely more in case of a LEO scenario, but the exact number cannot be determined with the available data). Similarly, taking into account that 5 Tankers should be launched to support each Mars trip and that each Tanker can be reused up to 100 times, at least 500 Tankers should be produced. At this point, taking into account the number of Raptor engines installed on each Super Heavy and Starship reported in Table 3 (for the Tanker, the same number envisaged for the Starship applies), a total number of 10,026 Raptor engines should be produced in order to equip all the vehicles involved in the Mars scenario. As mentioned, the same production numbers are preliminary assumed for the LEO scenario. Please, notice that the Tanker vehicle, envisaged only for the Mars mission, is not specifically tackled in this analysis. As far as learning curve is concerned, a learning factor of 0.9 is hypothesized for the Super Heavy, 0.7 for the Starship and 0.83 for the Raptor.

Table 6. Total Production costs summary for SpaceX Starship TSTO

	Governmental Scenario M€ [FY 2021]	**Commercial Scenario M€ [FY 2021]**
Raptor	29,057.87	10,170.25
1st Stage (no engines)	32,451.85	11,358.15
2nd Stage (no engines)	445,380.87	155,883.30
TSTO Vehicle	487,541	188,216

5.3.Space X Starship TSTO Operating Costs

Following the indications reported in Figure 1, the Operating Costs for the Space X Starship TSTO case study are estimated and reported hereafter. In addition, it is possible to estimate the average cost per flight and the cost per kg of payload released in LEO.

Table 7. Results – Space X Starship TSTO Operating Costs

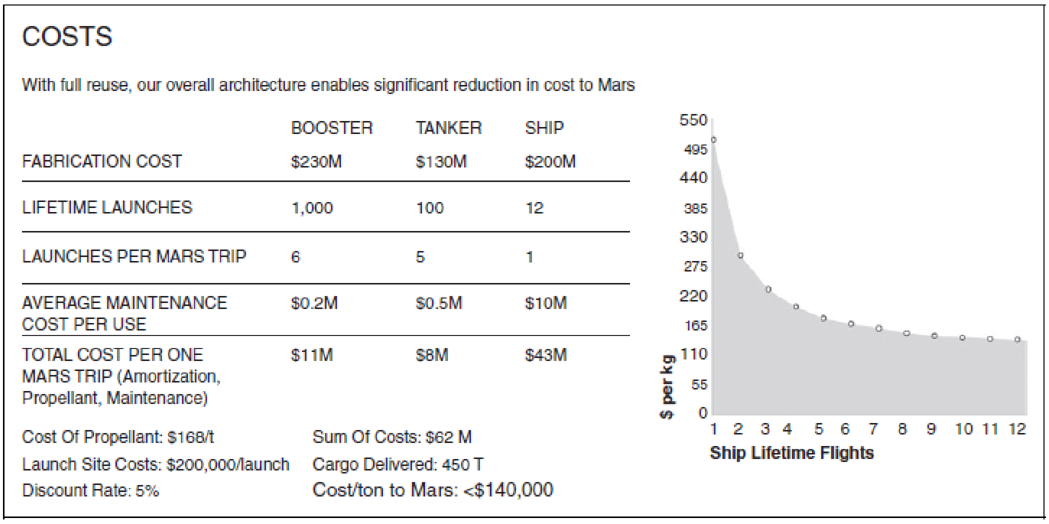
		Governmental Scenario M€ [FY 2021]	**Commercial Scenario M€ [FY 2021]**
RSC	**Amortization share of vehicle prod. cost**	47.30	16.55
	Rocket Engine RSC	0.0195	0.0195
	First Stage RSC	33.98	11.89
	Second Stage RSC	0.69	0.24
	Total RSC	34.69	12.15
DOC	**Ground Ops**	45.97	22.99
	Launch, Flight, Mission Ops	1.37	1.37
	Propellant Cost	0.76	0.76
	Launch Site User Fee	0	0.17
	Public Damage Insurance	1.42	1.42
	Mission Abort	4.21	2.59
	Vehicle Loss Charge	0.0820	0.0287
IOC	**Commercialization cost**	4.65	2.48
BUSINESS CHARGES	**RDTE cost amortization charge**	0	25.74

Table 8. Summary of Cost per Flights and cost per kg for SpaceX Starship TSTO

	Governmental	**Commercial**
DOC per flight [M€]	88.50	41.47
IOC per flight [M€]	4.65	2.48
RSC per flight [M€]	81.98	28.71
Cost per Flight [M€]	140.45	86.24
cost per kg [€/kg]	3511.15	2156.00

5.4. Results comparison with Space X official data

The costs estimated for this case study have been compared with available data from SpaceX. In particular, lacking specific cost data for a LEO mission, cost information for the Mars Mission reported in Fig. 6, has been considered. Notably, Fabrication Cost, Average Maintenance Cost per Use and Total Cost per one trip to Mars for the Booster (Super Heavy) and the Ship (Starship) have been verified. As already mentioned, the costs for the Tanker vehicle have been excluded from the present analysis. Please, notice that the cost data in Fig. 6, originally referred to FY2017, have been converted to FY2021. Examples of the comparison between estimated costs and reference Space X data are provided in Fig. 7. As it can be noticed, estimated values are in very good agreement with SpaceX projections.



COSTS

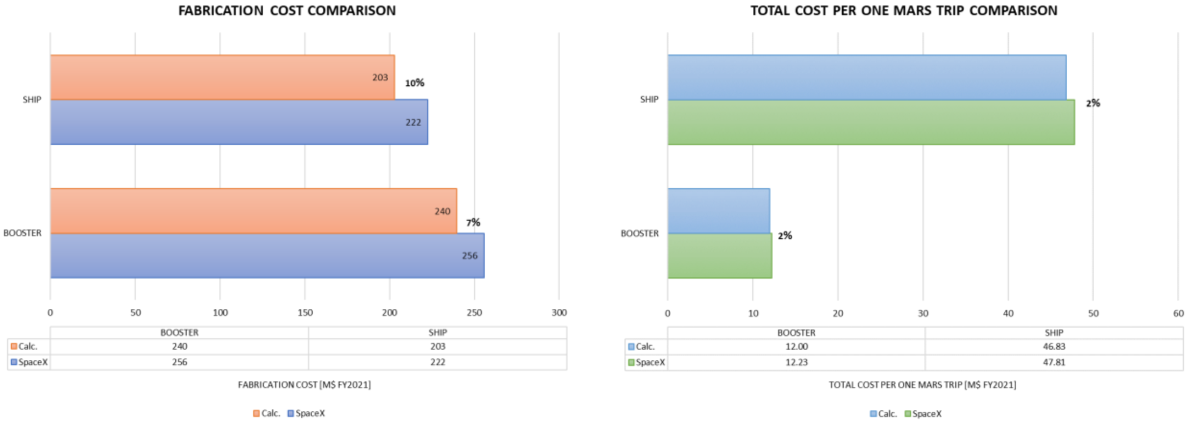
With full reuse, our overall architecture enables significant reduction in cost to Mars

	BOOSTER	TANKER	SHIP
FABRICATION COST	$230M	$130M	$200M
LIFETIME LAUNCHES	1,000	100	12
LAUNCHES PER MARS TRIP	6	5	1
AVERAGE MAINTENANCE COST PER USE	$0.2M	$0.5M	$10M
TOTAL COST PER ONE MARS TRIP (Amortization, Propellant, Maintenance)	$11M	$8M	$43M

Cost Of Propellant: $168/t
Launch Site Costs: $200,000/launch
Discount Rate: 5%

Sum Of Costs: $62 M
Cargo Delivered: 450 T
Cost/ton to Mars: <$140,000

Fig 6. Estimated cost of SpaceX Starship for the Mission to Mars [2]



	BOOSTER	SHIP
Calc.	240	203
SpaceX	256	222

	BOOSTER	SHIP
Calc.	12.00	46.83
SpaceX	12.23	47.81

Fig 7. (left) SpaceX Starship TSTO Fabrication Cost Comparison; (right) SpaceX Starship TSTO Total Cost per One Mars Trip Comparison

Conclusions

This paper has presented the upgrades to the HyCost methodology and tool to support the LCC for future reusable access to space vehicles since the early conceptual design stages. In particular, a thorough assessment of the available literature models allowed to identify the main gaps and ultimately the list of cost items for which new equations were required. The methodology laying behind the definition of the new set of CERs has been discussed together with the implementation in a software environment. The results of the application of the upgraded cost model to SpaceX Starship TSTO and the comparison with the preliminary data available in literature confirms the good agreement of the HyCost predictions.

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