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Cost Estimation for Innovative Space Systems: A Methodology for Microlaunchers and Inflatable Heatshields

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Abstract

Cost estimation for innovative space systems, such as microlaunchers and inflatable heatshields, presents significant challenges due to the lack of historical data and their complex and novel nature. In this paper, a cost estimation methodology for these systems is presented, which is based on the assumption that there may be similarities in the development and manufacturing costs among these systems.

The cost estimation methodology for microlaunchers considers the cost drivers at the subsystem level and the commercial nature of these systems. The methodology provides a tool for assessing the feasibility and profitability of microlauncher projects. The methodology for inflatable heatshields adapts the cost estimation methodology used for microlaunchers to account for the innovative nature of this technology. The methodology estimates the development and manufacturing costs of inflatable heatshields for future missions.

The research activity was part of various research projects, including collaborations with the European Space Agency (ESA) and projects funded by the European Commission in H2020 and Horizon Europe programs.

Overall, the cost estimation methodology for microlaunchers and inflatable heatshields provides a tool for assessing the feasibility and profitability of innovative space projects. The methodology can help provide rough estimates of costs, and its application can inform decision-making processes and improve the affordability of future space missions.

Keywords: cost estimation, innovative space systems, microlaunchers, inflatable heatshields

Acronyms/Abbreviations

Cost Estimating Relationships (CERs), Cost per Flight (CpF), Design and Development (DD), Flight Unit (FU), Inflatable Heat Shield (IHS), Launch Vehicle (LV), Manufacturing, Assembly, Integration, and Test (MAIT), Price per Flight (PpF), Rough Order of Magnitude (ROM), Technology Readiness Level (TRL), Theoretical First Unit (T1).

1. Introduction

The dynamic landscape of space exploration continually demands the evolution of technologies and methodologies underpinning the design and implementation of space systems and missions. In this context, the emergence of new stakeholders, particularly within the commercial sector, has introduced unique challenges and opportunities, compelling a revaluation and enhancement of existing processes.

This study is primarily centred on the assessment of a novel category of compact launch systems known as microlaunchers. These microlaunchers are unique in their commercial nature and their ability to transport payloads into orbit, with a capacity of up to 300 kilograms.

Furthermore, in a world increasingly emphasizing sustainability and efficiency in space exploration, the development and integration of transformative technologies like the inflatable heatshields (IHS), or inflatable heatshields, take on profound importance. These innovations hold the potential to enable the Earth recovery of launchers' upper stages and, crucially, to enhance Mars entry. This research includes a first order cost estimation for such systems seeking to address the evolving needs of the contemporary space industry in its innovative path [1].

In Fig. 1 an infographic underlines the magnitude of the commercial space activities (in yellow, [2]).

Fig. 1 Infographic showing the increase and change in nature of the space activity. Credits: ESA and UNOOSA [2]

2. State of the art

The shifting landscape of space exploration and missions has brought forth a marked transformation in the fundamental criteria guiding their design and execution. Where once the primary emphasis lay in the pursuit of maximum performance, the contemporary paradigm is increasingly defined by an unwavering focus on cost efficiency as the overarching design criterion. This transformation is propelled by the immutable constraints of limited resources and the inexorable participation of commercial actors to the industry, which have collectively erected more stringent economically barriers to be surmounted. Thus, the integration of cost considerations into every facet of mission planning and management decisions has become not only a strategic imperative but a vital necessity. Cost engineering, once relegated to the periphery, has now ascended to occupy a central and indispensable role in the early stages of space programs' inception, extending its influence throughout their execution.

The aerospace industry has undergone significant transformations, moving away from its traditional reliance on government-funded projects and embracing the dynamic realm of commercial ventures. This shift reflects the evolving landscape of aerospace, where markets have become the primary drivers of technological advancements, although governments continue to play a substantial role. Private companies, visionary entrepreneurs, and industry giants have all been enticed by the prospects of the space market, embarking on ambitious endeavours that have fundamentally reshaped the industry.

In this contemporary aerospace environment, the importance of cost estimation cannot be overstated. It permeates program management throughout the entire project lifecycle. The allocation of resources is not uniform across all project phases, with manufacturing and operations often requiring a significant portion of the budget. This underscores the need for continuous technological progress and the promotion of spacecraft hardware reusability, necessitating adjustments to existing cost models to accommodate these transformative changes.

The realm of cost estimation in the space sector is intricate, featuring a plethora of proprietary models and tools. These tools cater to various aspects of space missions, such as subsystems, space instruments, systems engineering processes, operations, processing, ground development, and risk assessments. The selection of appropriate estimation methods and tools is of utmost importance, as it profoundly influences the overall project costs. There is no one-size-fits-all approach, as estimation methods like parametric, analogous, and engineering techniques are chosen based on the project's development stage and data availability. These methods are flexible and often converge or are adapted to address the specific requirements of each mission and by no means mutually exclusive [7].

2.1 Cost Estimating Methodologies

At the nascent stages of project development, parametric cost models emerge as indispensable tools. These models are steeped in historical data, meticulously collected at an aggregated level, and are underpinned by mathematical techniques designed to establish Cost Estimating Relationships (CERs). They offer an invaluable solution, especially when program definition is rudimentary, and access to granular data is scarce. Parametric cost estimation has found wide-ranging applications, spanning both industry and government spheres, serving as a cost-effective approach grounded in cost and price data, albeit often restrained by the classified nature of projects in a fiercely competitive space industry.

Analogous cost estimation, by contrast, pivots on the foundational premise that new programs frequently emerge from existing programs or constitute amalgamations of existing components. This approach hinges on actual costs culled from akin past or ongoing programs, adeptly adjusted to account for complexity, technical nuances, or physical disparities. Analogous estimation assumes paramount importance when access to actual cost data is curtailed but is underpinned by a reasonable level of program and technical definition. Yet, the quest for suitable analogues and the acquisition of comprehensive data for validation can prove formidable challenges, thereby ensconcing this method in the realm of expert judgment.

Engineering build-up estimates, a stalwart of bottom-up estimation, preside over the meticulous aggregation of costs, individually estimated by each organization entrusted with the delineated tasks in the Work Breakdown Structure (WBS). These estimates, renowned for their precision, are nevertheless characterized by their labour-intensive nature and inherent susceptibility to iteration. Modifications, shifting assumptions, or the infusion of novel elements necessitate the creation of fresh estimates, thus rendering this approach ill-suited to the embryonic stages of projects marked by a paucity of substantive details.

Expanding the array of cost-estimating methodologies, expert judgment estimation emerges as a subjective yet invaluable instrument. This method leverages the collective expertise and knowledge of estimators, spanning both individual and group settings, with methodologies like the Delphi method or the Analytically Hierarchical Process (AHP) gaining prominence. Notably, it finds pervasive utility across all project phases, particularly in scenarios where historical data remains scarce. Despite facing critiques of subjectivity and potential bias, expert judgment remains ubiquitously employed within the domain of cost estimation.

Finally, the high-level estimation method known as Rough Order of Magnitude estimation, or vendor quote estimation, takes centre stage in the early phases of mission planning. Drawing upon past experiences or industry-wide data, this method generates preliminary cost assessments. While it proffers a first-order approximation, it serves as an invaluable tool for conducting initial cost evaluations [6].

In the context of practical application, the choice of cost-estimating method hinges upon several pivotal factors, including the extent of program definition, the requisite level of detail, data accessibility, and temporal constraints. For instance, during the embryonic stages of program development, characterized by the exploration of myriad conceptual options, a parametric model, reliant on limited program definition and exempt from the prerequisites of actual cost data, proves a judicious selection. As a program's design matures and actual cost data accumulates, an analogous approach assumes precedence. It is crucial to recognize that diverse projects may fluidly incorporate an array of these cost-estimating tools, artfully tailored to accommodate the distinct exigencies and timelines inherent to varying phases within the program lifecycle.

The effectiveness and flexibility of various cost-estimating methods are closely tied to several factors, including the program's phase, how well the program is defined, the availability of data, and the time constraints. In the dynamic landscape of the modern aerospace industry, mastering the complexities of cost estimation is paramount. Cost estimation is an essential yet intricate discipline, and its success relies on a delicate interplay of these factors. Moreover, most of the time, CERs are derived from conventional practices, often overlooking the novel manufacturing processes envisioned by emerging innovative space systems. It is imperative to develop an updated estimating methodology that can effectively accommodate the requirements of this evolving commercial space environment.

3. Methodology

This section details the cost estimation methodology developed for microlaunchers and extends it to inflatable heatshields. The methodology builds upon the approach developed by Drenthe [3] in collaboration with the European Space Agency (ESA) for small and commercial launch vehicles. The methodology is designed to provide flexibility, allowing the incorporation of new technologies and the refinement of estimates as more data becomes available.

3.1 Microlaunchers

Microlaunchers are designed for space access, capable of carrying payloads of up to 300 kilograms. The growing demand for launching small satellites has driven the exploration of small launchers to meet the specific needs of these lighter payloads. Traditionally, such small satellites were often secondary payloads on larger launch missions.

Several private companies have introduced intriguing concepts for microlaunchers; however, evaluating these concepts presents a challenge due to the limited availability and confidentiality of data. To effectively assess and compare the multitude of emerging concepts, the utilization of appropriate cost estimation tools becomes essential. Fig. 2 depicts the methodology logic and main problem aspects addressed in the work presented in this paper. The goal is a parametric cost estimating methodology, based on the subsystems mass and hardware cost considerations, that includes the commercial application influences.

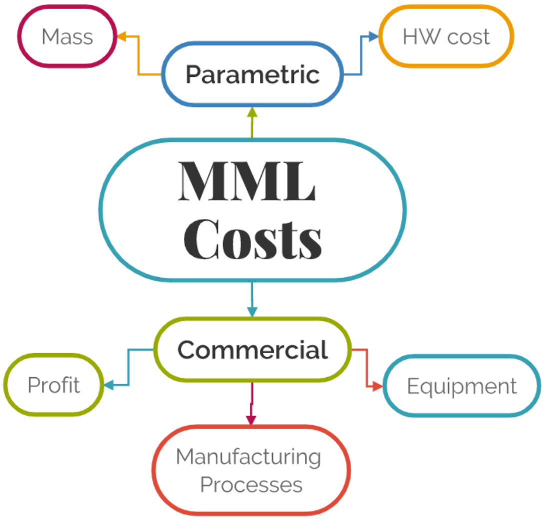


Fig. 2 Methodology approach to address the microlaunchers cost estimate

3.2 Theoretical First Unit (FU/T1) Approach

The research methodology commences with the breakdown of the launch vehicle, providing essential information about the masses of its subsystems. Subsequently, the cost of the first theoretical production unit, commonly referred to as the Flight Unit or Theoretical First Unit (FU/T1) costs, is ascertained. This estimation procedure is constructed based on historical data and is instrumental in predicting the costs associated with individual hardware constituents within the launch vehicle (see Fig. *3*).

Furthermore, the assessment of Non-Recurring Costs linked to the developmental phase of the rocket employs the FU/T1 costs and specific CERs (see Fig. 4). This estimation encompasses the customary expenses associated with System Test Hardware (STH) and the engineering efforts of Design and Development (DD) during the developmental stage.

Also, the recurring costs associated to manufacturing are based on the FU estimates. Only the operating costs are instead estimated through TRANSCOST model [8], allowing to determine the Cost per Flight (CpF) and the cost-based Price per Flight (PpF). These metrics facilitate a comparative analysis of the rocket's costs and pricing vis-à-vis its competitors and established industry benchmarks.

The concept of the Flight Unit (FU) or Theoretical First Unit (T1) represents a parametric approach to cost modeling, specifically tailored for estimating costs in the nascent stages of a project, characterized by a dearth of comprehensive data. The FU/T1 approach enables the computation of the cost associated with the initial theoretical production unit of the system or vehicle by leveraging data driven CERs and parametric models. It serves as a fundamental benchmark for approximating non-recurring costs during the developmental phase and evaluating potential cost enhancements during the manufacturing process.

The FU/T1 concept is employed at the equipment level of the rocket system. The extent of this breakdown is contingent on the specific category of the system under scrutiny and the accessibility of cost data pertinent to the type of system being analyzed. While a more detailed breakdown is conducive to a comprehensive bottom-up cost estimation, it may become impractical due to data availability. Conversely, a more cursory breakdown, though less time-consuming, may lack the requisite granularity to encompass system-specific adaptations pertinent to commercial and small-scale launch vehicles.

Fig. 3 Microlaunchers cost methodology flow

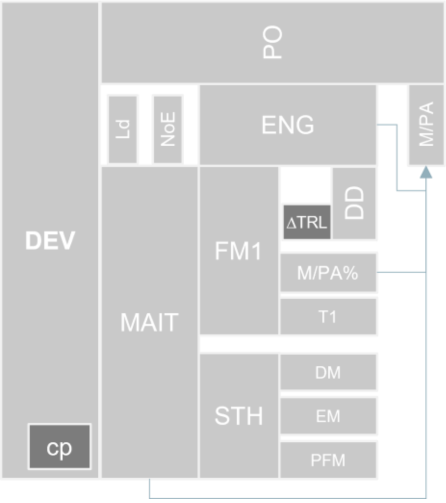


Fig. 4 Development cost drivers

3.4 Development Costs

Estimating the efforts required for microlauncher development during the early phases presents challenges due to limited knowledge of mission parameters, configuration, and environmental factors. To overcome these challenges, a heuristic approach is employed, incorporating modifiers based on historical data from analogous systems using Theoretical First Unit equivalents [8].

The approach involves modeling major components of development costs as multiples of the Flight Unit (FU/T1) costs. These T1 costs are augmented with modifiers that depend on the amount of hardware tested and the engineering effort required for the development of specific subsystem elements.

The estimation of engineering (ENG) development costs employs a Design and Development (DD) T1 equivalent value (see Fig. 4). This facet of the methodology proves to be highly innovative and significantly noteworthy. In the context of pioneering systems like microlaunchers, the capability to account for the expenses associated with developing cutting-edge technologies, which are often in the early stages of Technology Readiness Level (TRL), holds paramount importance.

One of the distinctive strengths of this model is its adeptness at considering costs tied to the advancement of technologies that are integral to a concept, even when these technologies are at a nascent stage in terms of TRL. By employing this methodology, it becomes feasible to evaluate and quantify the requisites for the development of individual subsystems or equipment, for instance if considered a novel, more environmentally friendly propulsion system.

3.4.1 System Test Hardware

The System Test Hardware models are assigned specific work efforts proportional to the Theoretical First Unit (T1) cost. The development model, including structural and thermal components, incurs an effort of 30% of the T1 cost. The Engineering Model (EM) requires the same resources as the T1, plus the involvement of test facilities and personnel, resulting in EM = 1.3T1. The Qualification Model (QM) has identical hardware to the First Flight Model (FM) and similar costs but involves a more resource-intensive testing campaign. Finally, the FM, equivalent to T1, is the first unit produced.

In some scenarios, a protoflight approach may be adopted to reduce costs, involving the reuse of the QM as a PFM (Protoflight Model), which is marginally more expensive due to necessary refurbishments.

3.4.2 First Flight Model (FM1)

To isolate hardware-related expenses and account for variations in management and product assurance costs associated with commercial applications, the FM1 cost element is defined. It is calculated by subtracting the Management & Product Assurance (M/PA) percentage from the T1 cost, ensuring that development costs are accurately allocated.

3.5 Manufacturing Costs

Manufacturing costs are a significant portion of the total Life Cycle Costs (LCC) of launch vehicles, often reaching up to 75%, depending on the number of units produced. Estimating manufacturing costs accurately is critical to mitigate overall program cost risk.

Manufacturing costs are divided into two major components: Manufacturing, Assembly, Integration, and Test (MAIT), and Management & Product Assurance (M/PA) activities. These costs are modelled as level-of-effort expenses, depending on the activities they support. The manufacturing phase is characterized by learning effects, where cost improvement is achieved as more units are produced. Learning curve analysis is employed to model unit cost reduction during production, following the unit theory learning curve.

3.6 Operating Costs

The launch operations campaign constitutes the recurring costs associated with preparing the rocket for launch and conducting launch operations until the stages are successfully disposed of. This section excludes Mission Operations costs. The TRANSCOST model by Koelle [8] is employed to estimate operating costs due to the lack of available data.

3.6 Cost and Price per Flight

The Cost per Flight (CpF) is calculated by combining development costs, manufacturing costs, and operations costs. The development cost is amortized over the total number of flights to obtain the development charge per unit, facilitating the conversion of CpF into a unit Price per Flight (PpF).

PpF represents the amount for which a launch is sold to a customer and includes development costs, ensuring cost recovery for the launch service provider. It's important to note that commercial enterprises may receive government funds to cover their development costs.

The calculation of CpF and PpF allows for a comprehensive assessment of the financial aspects of launching microlaunchers, enabling comparisons with publicly available launch price quotes and supporting informed decision-making in project planning and resource allocation.

4. Application to Microlaunchers

In the realm of microlaunchers, a specific launch vehicle was selected as subject of study. Such selection was dictated by generously shared detailed information about its launchers, setting it apart from other projects in the same category. Moreover, the chosen launcher intent to leverage metal 3D printing technology for the manufacturing of rocket engines. Given the significant impact of incorporating such an innovative production method into the cost estimation process and the relatively limited availability of data in this domain, this study centres its focus on a comprehensive analysis of this specific microlauncher.

The cost estimates derived from this study estimations are compared with cost data of similar launch systems (see Fig. 5). It is essential to acknowledge that the data and information used for this cost estimation endeavour are selected based on the available resources and industry disclosed information. The estimates inherently carry limitations and uncertainties associated with the data used.

In the ensuing sections, we embark on an in-depth exploration of the cost estimation analysis, delving into the intricacies of development, manufacturing, and operating costs that shape the financial landscape of this microlauncher.

The cornerstone of the cost estimation process revolves around the Theoretical First Unit (FU/T1) cost. To derive this crucial parameter, specific vehicle data, not publicly available, had to be meticulously obtained. To achieve this, we harnessed advanced modelling techniques, employing commercial software such as EcosimPro or Astos. This advanced modelling approach allowed us to generate the requisite data for our calculations when such data is not publicly available. These data-driven inputs serve as valuable additions to our cost estimation model, seamlessly integrating into the framework established through an ESA contract. Indeed, the cost estimation model was implemented in the Qt environment using the Python coding language, resulting in an interactive graphical user interface (GUI). Such software implementation, undertaken during the ESA Contract named iDREAM, facilitates user-friendly access to the model and methodology [9].

Estimating the engineering costs associated with development is a nuanced task, intricately intertwined with the Technology Readiness Level (TRL). In our case, we adopt a parameter defined as $3+\Delta(\mathrm{TRL})$, accounting for the variance in TRL from the baseline. For the launcher under study, a TRL difference of 2 is assumed for the rocket engine, grounded in its ambitious manufacturing goals involving 3D printing, bio propellant utilization, and the fed system. The current TRL, as of our analysis, is set at 5. Moreover, in contrast to the baseline, we maintain a learning factor of one for engine development, acknowledging the peculiar characteristics of 3D printing and its relatively flat learning curve.

Notably, despite the absence of certain advantages linked to the learning factor and the requisite TRL achievement, the launcher differentiates itself by its markedly lower mass in comparison to other launchers, while retaining a similar payload capability (200 kg - 300 kg payload mass). This unique feature contributes significantly to its cost competitiveness, although the accuracy of this outcome hinges on the credibility and transparency of the owner's data regarding engine mass.

4.2 Manufacturing Costs

Manufacturing costs entail careful consideration due to the distinctive characteristics of the rocket engine produced through 3D printing. Unlike conventional manufacturing processes, where learning curves play a substantial role in cost reduction over time, 3D printing tends to exhibit an almost flat learning curve, signifying minimal improvements. To accommodate potential advancements during the production of 50 units, we apply a learning factor of 99% for 3D printing operations. In contrast, other elements of the launcher, manufactured through conventional means, assume a baseline learning factor of 90%, resulting in more pronounced cost reduction per unit.

Innovative manufacturing processes, such as 3D printing, offer distinct advantages and challenges. While conventional processes excel in large-scale manufacturing due to cost-efficiency, 3D printing shines in quick prototyping and low-volume production of intricate geometries. The choice of material, coupled with the production technique, contributes to increased complexity. Future projects may further explore this factor by comparing data for similar equipment produced via different techniques or materials.

4.3 Operating Costs

Operating cost estimation relies on TRANSCOST CERs [8], albeit with certain complexities due to the lack of operational data for the launcher under study. The total operating cost are validated with other case study in existing literature.

Ground Operations, a key component of operating costs, consider the cost reduction factor associated with the learning curve. However, this factor warrants reconsideration in light of the unique aspects of 3D printing and the potential expedited production schedules it enables. Additionally, propellant cost considerations, based on the use of Liquid Petroleum Gas (LPG) and its specific cost per kilogram, factor into the operational cost analysis.

4.4 Cost, Price, and Specific Costs

The ultimate cost per flight comprises an amortization charge that distributes development costs across all manufactured units. Moreover, the Price per Flight incorporates a profit margin set at 8%, aligning with typical values for commercial enterprises.

When considering larger payload capability, more than 1000kg, the launchers compared follow more closely a trendline. This changes drastically when considering the small launchers for which a specific cost k€/kg it is still hard to define (see Fig. 5). The advertised price per flight instead seems following in a more regular pattern with respect to the payload capability (see Fig. 6).

Although some results may show a not significant competitiveness of the microlaunchers when juxtaposed with other commercial launcher, its niche access tailored for small satellites missions, may offset the relatively higher specific cost.

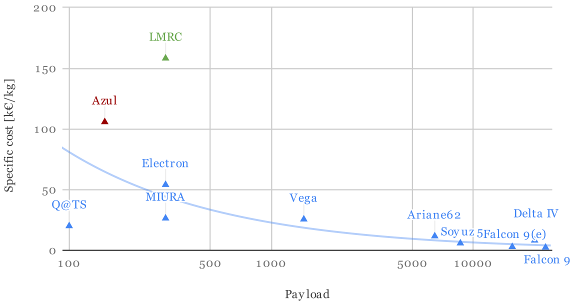


Fig. 5 Specific cost [k€/kg] vs Payload [kg]

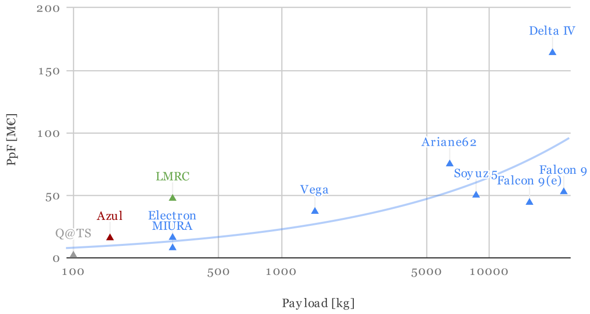


Fig. 6 Price per Flight (PpF) [M€] vs Payload [kg]

4.5 Sensitivity

A sensitivity analysis is conducted on the engine mass of studied launcher to assess the significance of this parameter. Indeed, the manufacturer claims a very low value if compared with other launchers. While manufacturing costs are most significantly affected, hardware costs follow closely. Despite the substantial manufacturing cost increase in the worst-case scenario (a 25-fold increase in engine mass), the total cost and price per flight exhibit a more gradual increase, reflecting the slower growth in development costs and the constant nature of operating costs. The cost per flight curve overlaps the price per flight curve as they are affected in the same way (see Fig. 7).

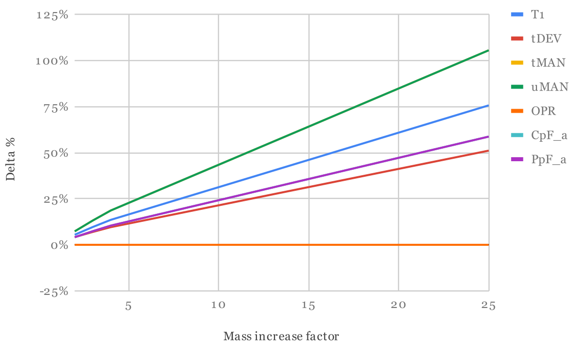


Fig. 7 Sensitivity analysis on input data for the rocket engine mass.

5. Application to Inflatable Heatshields

This section elucidates the cost estimation conducted in the context of a Business Case Analysis (BCA) for the Inflatable Heat Shield (IHS) technology, as part of the EFESTO and EFESTO-2 projects. IADs represent an innovative solution for re-entry vehicles, offering advantages such as increased payload mass or higher altitude landings while reducing stowed volume and mass compared to rigid heatshields [5]. Moreover, it may allow the recovery of launch vehicles' upper stage. However, the complexity of IHS systems, encompassing flexible structures, Flexible Thermal Protection Systems (F-TPS), and inflatable structures, introduces challenges related to re-entry flight, delivery accuracy, and thermal limits. The BCA aimed to assess market opportunities, performance requirements, cost estimates, and profitability of the IHS technology. IHSs hold promise for various applications in space exploration, including space hardware reusability, Mars colonization, and space mining. Moreover, they play a pivotal role in enabling launcher stage recovery, reducing space debris, and minimizing environmental impacts.

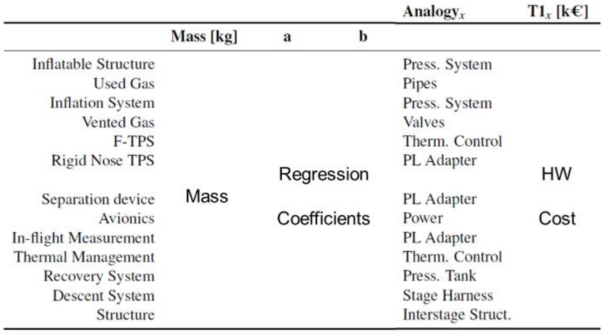
5.1 Rough Order of Magnitude (ROM)

To estimate the development costs of the EFESTO IHS technology, a simplified approach is employed first. It leverages costs associated with the EFESTO and EFESTO-2 projects, extrapolating from the expected maturity level at the end of each project, the development achieved, and the funding received ([10], [11]). This allows to obtain an approximation of the development costs for the inflatable heatshield, including the crucial development of the inflatable structure and the Flexible Thermal Protection System (F-TPS) of the HIS.

5.2 Development and Manufacturing Life-cycle Phase Cost Estimation

The cost estimation for the development and manufacturing life-cycle phases of the Inflatable Heat Shield (IHS) system follows the previously outlined methodology. Considering the mass values of subsystems and providing a detailed breakdown of the IHS system, the estimation process leverages the Theoretical First Unit (T1) estimates, which are derived through the application of mass-cost Cost Estimation Relationships (CERs) and regression coefficients based on historical data.

The mass values for the subsystems are obtained from the design effort conducted during the project. However, it's essential to highlight that historical data for the IHS system are not available for estimating the T1-equivalent. To address this data gap, this study has employed a correlation with historical data from launchers. This approach enabled us to apply the methodology and conduct a preliminary cost estimation for the IHS system. A sensitivity analysis was performed by varying the correlation, resulting in variations within an acceptable range of approximately 10%. This level of variation is considered quite reasonable, especially for a preliminary study of this nature. In Fig. 8 an example of IHS and launcher's components correlation.



	Mass [kg]	a	b	Analogy$_x$	T1$_x$ [k€]
Inflatable Structure	Mass	Regression Coefficients		Press. System	HW Cost
Used Gas				Pipes	
Inflation System				Press. System	
Vented Gas				Valves	
F-TPS				Therm. Control	
Rigid Nose TPS				PL Adapter	
Separation device				PL Adapter	
Avionics				Power	
In-flight Measurement				PL Adapter	
Thermal Management				Therm. Control	
Recovery System				Press. Tank	
Descent System				Stage Harness	
Structure				Interstage Struct.	

Fig. 8 IHS and Launch Vehicle components correlation

The obtained estimation includes, building and testing activities, and overhead level-of-effort costs such as management and product assurance. The estimation includes fixed costs (development of IHS and for the launch vehicle's stage and necessary LV upgrades) and recurring costs (Manufacturing, Assembly, Integration, and Test (MAIT), and operations).

5.3 Validation

A comparison between the Rough Order of Magnitude (ROM) cost estimation, which is based on the development funds received and the cost of the prototype hardware, and the development costs derived using the presented methodology reveals a reasonable alignment between the two estimates, demonstrating a consistent outcome with a deviation of approximately 17%.

Furthermore, the DLR team of the EFESTO Consortium conducted a manufacturing cost assessment for a specific study case, focusing on a launcher equipped with a reusable upper stage employing Inflatable Heat Shield (IHS) technology. The results obtained from their assessment closely correspond to the manufacturing cost estimation developed in this study, thus validating the reliability and accuracy of the cost assessment approach employed, with a deviation of approximately 4%.

These estimations offer valuable insights into the economic feasibility of utilizing IHS technology for re-entry vehicles and upper stage reusability. Moreover, the alignment of the methodology and results with external assessments serves to reinforce the validity of the approach and the consistency of the results.

6. Discussion

The case study of the Inflatable Heat Shield (IHS) serves as a compelling validation of the developed cost estimation methodology presented in this research. The remarkable congruity between the estimates derived from the methodology and the Rough Order of Magnitude estimate based on actual funding costs attests to the effectiveness of the approach employed. It is important to acknowledge that the methodology relies on certain assumptions, particularly regarding the comparability of hardware costs between IHS equipment and analogous launcher equipment. While these assumptions may seem less intuitive, the use of regression coefficients derived from normalized data provides a reasonable order of magnitude for cost estimation. An alternative pairing of mass-cost data for IHS and launcher equipment demonstrates only a marginal difference, falling well within the expected uncertainty boundaries for an early-stage analysis. To enhance the methodology's robustness further, conducting a sensitivity analysis to explore alternative data pairings could reduce uncertainty in cost estimates and their ranges.

The primary objective of this research project was to develop cost estimation methodologies tailored to meet the evolving needs of the space industry, particularly in the context of its commercialization. These methodologies have the potential to offer valuable processes and methods to systems engineers engaged in the development of innovative systems. By providing a structured framework, these methodologies enhance the decision-making process and assist in identifying optimal solutions aligned with the objectives and constraints of the space industry. It addresses the challenges posed by the evolving commercial landscape of space applications, optimized resource allocation, and advancement of the space industry as a whole.

7. Conclusions

This research project has systematically explored methodologies for decision-making and cost estimation across various innovative space systems, ranging from microlaunchers at the system level to the Flexible Thermal Protection System (F-TPS) of an inflatable heatshield at the technology level. The outcomes of these investigations have undergone extensive discussions with stakeholders and, in some instances, translated into tangible prototypes that successfully underwent hardware testing. The incorporation of innovative manufacturing techniques proposed by commercial participants in the new space industry underscores the adaptability and value of the analogy cost estimating method, even in the face of limited available data and a growing number of commercial competitors in lunar exploration.

There are currently ongoing activities to address the study limitations and implementing new technology insights for the innovative space systems considered.

For confidentiality reasons in alignment with the current project stage, the specific numerical results have been excluded from this discussion. However, it is important to note that we intend to release and share all numerical values in forthcoming publications as soon as permissibility allows.

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References

[1] G. Governale, Technical Management Processes: Trade-off Analysis and Cost Estimation for Innovative Space Systems, PhD Thesis, 2023.
[2] UNOOSA, Space Sustainability: Stakeholder Engagement Study, https://www.unoosa.org/oosa/en/informationfor/media/unoosa-and-esa-release-infographics-and-podcasts-about-space-debris.html
[3] N. T. Drenthe, Cost estimating of commercial smallsat launch vehicles. Acta Astronautica, 2017.
[4] G. Governale, J. Rimani, N. Viola, and V. Fernandez Villace. A trade-off methodology for micro-launchers. Aerospace Systems, 2021.
[5] G. Guidotti, F. Trovarelli, A. Princi, J. Gutierrez-Briceno, G. Governale, N. Viola, I. Dietlein, S. Callsen, K. Bergmann, J. Zhai, T. Gawehn, R. Gardi, B. Tiseo, Y. Prevereaud, Y.Dauvois, G. Gambacciani, G. Dammacco, "EFESTO-2: European Flexible Heat Shields Advanced TPS Design and Tests for Future In-Orbit Demonstration - 2", Aerospace Europe Conference 2023 - 10th EUCASS - 9th CEAS Conference, Lausanne, 2023.

[6] O. Trivailo, M. Sippel, Progress in Aerospace Sciences Review of hardware cost estimation methods, models and tools applied to early phases of space mission planning. 53:1–17, 2012.

[7] National Aeronautics and Space Administration, Expanded Guidance for NASA Systems Engineering Volume 1: Systems Engineering Practices, volume 1. 2016.

[8] D. E. Koelle, Handbook of Cost Engineering for Space Transportation Systems with Transcost 7.2: Statistical-analytical Model for Cost Estimation and Economical Optimization of Launch Vehicles, 2007.

[9] R. Fusaro, N. Viola, G. Narducci, G. Governale, et all, “IDREAM: a multidisciplinary methodology and integrated toolset for flight vehicle engineering”, 73rd International Astronautical Congress 2022, Paris, 2022.

[10] Cordis EU Research Results, European Flexible hEat Shields: advanced TPS design and tests for future in-Orbit demonstration, June 2023, https://cordis.europa.eu/project/id/821801

[11] Cordis EU Research Results, European Flexible hEat Shields: advanced TPS design and tests for future in-Orbit demonstration-2, October 2022, https://cordis.europa.eu/project/id/101081104