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iDREAM: a multidisciplinary methodology and integrated toolset for flight vehicle engineering

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Abstract

Rapid prototyping of flight vehicle engineering needs the use of two key elements: the data from the different building blocks and the required engineering tools to design vital subsystems of the flight vehicle. Politecnico di Torino in the framework of the I-DREAM, a GSTP contract carried out under the supervision of the European Space Agency (ESA), has developed a unique multidisciplinary methodology and integrated toolset able to support the rapid prototyping of a wide range of aerospace vehicles. iDREAM allows complementing the conceptual design activities with the economic viability and technological sustainability assessments. In detail, the iDREAM methodology consists of four main modules that can be used in a stand-alone mode and in an integrated activity flow, exploiting the implemented automatic connections. The first module consists of a well-structured MySQL database developed to support all the other modules, thanks to a unified connection guaranteed by an ad-hoc developed Database Management Library managing the operations of data input and output from/to the database throughout the tool modules. The second module consists of a vehicle design routine and a mission design routine, supporting the design of a new vehicle and mission concept and assessing the main performance of an already existing configuration. The vehicle design routine is called ASTRID-H, and it is the latest version of an in-house conceptual design tool integrating capabilities ranging from high-speed aircraft to lunar-landers design. The vehicle design routine automatically interfaces with ASTOS, a commercial software environment used for mission analysis optimization. Automatic interactions between the two routines inside the module have been ad-hoc developed and tested to guarantee good accuracy of the results. The third module consists of the economic viability module. Once the design is defined, it is possible to run a subsystem-level cost estimation. Using the subsystems' masses estimated in the design routine, the parametric cost model provides useful insights on the potential development, manufacturing, and operating costs, as well as the cost and price per flight. Eventually, the developed methodology gives the possibility to generate a technology roadmap (fourth module). Supported by a database connection, the tool estimates each technology readiness and risk assessment, along with an indication of the necessary activities, missions, and future works. This paper describes the methodology and the integrated toolset in flight vehicle engineering of Microlaunchers. Eventually, the Electron mission would be used as a benchmark and validation study to showcase the tool's results and accuracy for preliminary design studies.

Keywords: Rapid Prototyping, Multidisciplinary Design Tools, Aerospace Vehicle Design, Technology Roadmaps, Cost Estimation

1. Introduction

With the boom of a new space economy era comes the need for tools that can rapidly prototype, and asses performances, schedule and cost of the new space building blocks. As in [1], [2], investors, companies and space agencies look for tools to help them size new systems or assess the feasibility of other proposed designs. These tools can help space agencies establish a strategic investment scheme to mature faster technologies related to the relevant new space economy systems like small satellites, microlaunchers and lunar surface elements. In this very challenging context, Politecnico di Torino (PoliTO) with the financial support of Italian Space Agency (ASI) and European Space Agency (ESA), started developing an integrated multidisciplinary methodology for rapid design of Microlaunchers (ML) [2], [3] and Lunar Lander (LL) [4] that would be soon extended to other vehicles. The methodology and related tools have been funded in the framework of the ESA General Support Technology Programme (GSTP) with the financial and technical support of ASI. This paper details the application of the PoliTO rapid-prototyping methodology to the ML case study.

The ML methodology designed by PoliTO couples the conceptual design of new vehicles with a thorough assessment of the economic and technological viability of the solution. As far as the economic viability is concerned, the vehicle Life-Cycle-Cost (LCC) is estimated with a parametric model based on Cost Estimation Relationships (CER)s. The inputs for these parametric CERs are the vehicle design variables and performance estimated during the conceptual design routine. Complementary to the cost estimation, the methodology introduces an assessment of the technological viability of the solution thanks to Technology Readiness Level (TRL) evaluation and the generation of a technology roadmap.

By definition, technology roadmapping methodologies are meant to support the identification of enabling technologies along with the activities required to pursue technology development, operational capabilities and building blocks, on the basis of well-defined performance target [5] [6].

This paper specifically aims to describe this methodology developed and implemented by Politecnico di Torino in an integrated software application called Integrated Design Roadmapping and Engineering stand-Alone Module for high-speed vehicle (iDREAM). The methodology steps are presented following the modules of iDREAM applied to the design of a microlauncher. According to several investigations, the microlauncher market is expected to be worth up to €410 million, even though few such systems have been developed [7], [8]. Their primary employment is to provide a dedicated launch vector to smaller payloads, like small satellites. Currently, these small satellites ride as piggyback of primary larger payloads [9] and must adapt to whichever orbital position they are deployed into. Unfortunately, this situation represents a constraint for the mission, especially regarding target orbit, design, and schedule.

Therefore, one of the design capabilities of iDREAM focuses on the design of new ML and on the validation of existing ML design. The PoliTO methodology provides a preliminary design of the microlaunchers from a given payload mass and assesses the solution's economic and technological feasibility. Therefore, the iDREAM methodology can be described as an integrated analysis framework encompassing the three main capabilities listed hereafter:

1. Design and related mission analysis of the analyzed vehicle called Aerospace on-board Systems sizing and Trade-off analysis in Initial Design (ASTRID-H).
2. LCC assessment named HyCost.
3. Conceptualization of related technology roadmaps for the identified design critical technologies called Technology Roadmapping Strategy (TRIS).

As schematically reported in Figure 1, iDREAM is developed (i) to accept input data directly inserted from users and (ii) to allow connections with ad-hoc structured databases. Thus, iDREAM allows the exploitation of the tools (ASTRID-H, HyCost, TRIS) and their capabilities as stand-alone modules or in the integrated framework.

The remaining of the paper is organized as follows: (i) Section 2 briefly introduces previous work undertaken by PoliTO on aerospace system design, cost assessment and roadmaps, (ii) Section 3 focuses on the iDREAM framework with an in-depth analysis of the methodology and the tool applied to the design of microlaunchers, (iii) Section 4 focuses on the design provided as output by the tool and its validation with a real case study, (iv) Section 5 provides focus on the

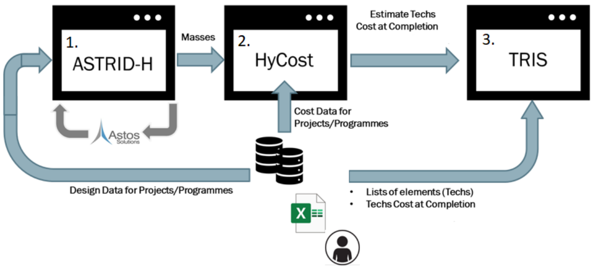


Figure 1: *Overview of the iDREAM integrated framework.*

main conclusions, lesson learned and future works on iDREAM.

2. Related Work

Rapid prototyping and multidisciplinary and integrated design methodologies and tools gained huge momentum in the aerospace industry in a variety of applications [10]–[15]. Multidisciplinary design tools provide the possibility to rapidly assess the main performances of different designs by iterating between different mission architectures.

The iDREAM methodology differs from the above-cited rapid prototyping processes because, in addition to the multidisciplinary aspects involved in vehicle design, iDREAM pursues a holistic approach by complementing the vehicle design with economic and technological feasibility aspects.

Moreover, iDREAM uses the stakeholder's needs and mission requirements as primary drivers in the design. The strong background in system engineering of PoliTO built up a strong foundation for the three tools that compose iDREAM [16]–[19]. More in detail, iDREAM builds on the capabilities of ASTRID-H a proprietary tool of PoliTO developed for almost a decade through research activities, encompassing Master of Science and Doctoral Theses [19]–[21]. ASTRID-H allows to carry out the conceptual and preliminary design of different aerospace systems. Originally, it provided an environment for the sizing and integrating subsystems for a wide range of aircraft, from conventional to innovative configurations, mainly in the subsonic, supersonic and eventually hypersonic speed regime. With iDREAM, its multi-fidelity design capabilities have been extended to microlaunchers and lunar landers. ASTRID-H has been validated through the application to various case studies in several European Commission-funded international projects, including the H2020 STRATOFLY (Stratospheric Flying Opportunities for High-Speed Propulsion Concepts) [16], [22], [23]. Another proprietary tool of PoliTO that has been upgraded and integrated in iDREAM is HyCost [24]–[26]. The tool has been developed in different ESA funded projects. It aims to estimate the LCC of a wide range of high-speed and suborbital vehicles with CERs based on the expected system performances. iDREAM benefits as well of TRIS , an innovative methodology for the generation and update of technology roadmaps to support strategic decisions for a wide range of aerospace products, developed in 2015 by PoliTO in cooperation with ESA [27]–[30].

All these tools merged in the iDREAM's supporting methodology can rely on a connection with an in-house developed database named HyDat. HyDat was originally developed to specifically support technology roadmapping activities of ESA for hypersonic transportation systems and Reusable Access to Space Vehicles [30].

3. The iDREAM Design Methodology

As previously introduced, the iDREAM integrated design environment is based on three main capabilities: (i) supporting the conceptual and preliminary design of aerospace systems, (ii) supporting as LCC assessment of the studied system, (iii) supporting technology roadmapping capabilities.

The first capability takes the form of ASTRID-H. The tool has been upgraded to support the design of microlaunchers, with the technical support of ESA. In particular, the ASTRID-H applied to microlaunchers can support two different types of analysis: (i) it allows the assessment and verification of an already existing microlauncher designs, (ii) it guides the users through the definition of a new microlauncher designs and reference mission scenarios starting from a set of high-level requirements. The tool can be easily integrated with a dedicated commercial software tool, Analysis, Simulation and Trajectory Optimization Software for Space Applications (ASTOS) [31]. ASTOS perform mission analysis studies assessing the performances of microlaunchers on relevant trajectories. Those mission analysis results are then reintegrated in the iDREAM framework to improve the accurancy of the overall vehicle design.

The second capability is actualized in HyCost. The tool can provide insights into the potential development, manufacturing, and operating costs, as well as the cost and price per flight from the design routine inputs or from an available user's database. The CER parameters are suggested by iDREAM, including reduction factors for commercial applications or variable learning factors for innovative manufacturing processes. To extend HyCost to this new case study, several cost estimation methodologies available in the literature have been investigated. Specifically, [32] developed a cost estimation methodology with ESA considering small and commercial launch vehicles. The method is based on the concept of the recurring first unit and it exploits linear factors that are applicable at subsystem and equipment levels. The methodology in [32] is considered the best fit for iDREAM since the cost estimates at the subsystem level allow greater flexibility in considering new technologies. The simple and intuitive relationships in the cost estimations enable to reach a good level of accuracy with respect to already developed systems thanks to the cost considerations at the subsystem level. Moreover, the cost estimations can be easily refined and updated once new data about these innovative launchers are released. The final updated model of LCC for microlaunchers used in iDREAM is detailed in [2]. It extends the work of [32] not only in the application but by implementing cost considerations regarding also manufacturing techniques and processes.

The last capability benefits of the TRIS methodology. More in detail, the TRIS methodology is fully integrated into up-to-date conceptual design activity flows. It consists of five main steps that through mathematical and logical models move from stakeholders' analysis up to planning definition and results in the evaluation. The overall flow is shown in Figure 2. Complementary to the traditional experts-based methodologies, the rational process of TRIS allows for a well-structured logical definition of activities and/or missions required to enhance the readiness level of technologies, including a more accurate and reliable budget and time resources estimation to support the technology development plan. More recently, to include a high-speed vehicle for point-to-point transportation, this methodology has been exploited in the framework of the H2020 STRATOFLY Project to assess the potential of hypersonic civil vehicles to reach Technology Readiness Level 6 by 2035 concerning key technological, societal and economical aspects [6].

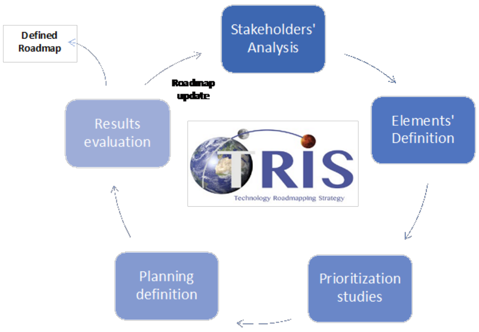


Figure 2: *TRIS methodology steps.*

Each of the briefly described tools has been implemented in a Python environment with a dedicated integrated Graphical User Interface (GUI).The user can access the integrated iDREAM tool as well as ASTRID-H, HyCost and TRIS as standalone tools from this GUI.

After this general overview of iDREAM the next subsections detail the main mathematical models behind the microlaunchers' design and roadmaps methodology.

3.1 The Vehicle Design Routine

The ML design methodology follows a top-down approach. Starting from the high-level requirements, the tool estimates the launcher characteristics thanks to five main modules: the mass estimation detailed in subsection 3.1.1, the propulsion system detailed in subsection 3.1.2, the dimensions estimation detailed in [2], the aerodynamics models detailed [2], and the preliminary mission design routine detailed in subsection 3.1.3.

These modules work iteratively to obtain the launcher performance, masses and main dimensions as well as aerodynamic and propulsive characteristics. Once the preliminary design analysis is completed, a first reference trajectory is studied in ASTRID-H to iterate the design. Finally, the output of the design routine is again re-refined and validated through the ASTOS software, performing a detailed mission analysis assessment and optimizing the estimated masses.

Suppose the users want to assess the feasibility of an already existing microlauncher design. In this case, they need to input some preliminary mission data in the design routine, such as the target orbit, the desired launch site, the total mass at launch, and the payload mass. Moreover, they should input the details of the analyzed vehicle configuration like the number of stages, propellant characteristics, the number of engines and the nominal lift-off mass. As shown from the activity workflow of Figure 3, those inputs can be derived from an Structured Query Language (SQL) database developed from known microlaunchers called Hydat [33].

After this set of inputs is provided to the design routine, the mass breakdown of the different vehicle stages can be evaluated with an optimal staging algorithm as shown in Figure 3. The algorithm estimates the propellant and inert masses of the different stages from the known target orbit and payload mass. Then, the tool assesses the propulsive system's expected performance and provides a first estimate of the general dimensions of the stages. The overall size and length of the microlauncher are then used to elaborate a first guess of the system's aerodynamic characteristics, particularly the drag coefficient. ASTRID-H integrates in its software architecture a preliminary mission design routine to generate a preliminary but accurate estimation of the required ΔV derived from the user inputs.

After the preliminary sizing of the vehicle is finished, ASTRID-H interacts with ASTOS to optimize the microlauncher design in terms of propellant and payload mass.

If the users are studying a new design for a microlauncher, they need to introduce similar inputs in the design routine as for the existing design assessment routine. In this case, inputs like the expected mass at launch or the vehicle length are not required. Instead, those values are directly estimated in the design routine. The new design study usually needs more iterations inside ASTRID-H to minimize the total mass before entering the ASTOS routine.

Some of the mathematical models behind the design provided by ASTRID-H have been already detailed in [2]. Therefore, the following sections of the paper would focus on the new refined models developed after [2].

3.1.1 ASTRID-H Mass estimation module

As the name suggests, this module allows the estimation of the main launcher mass. There are two different staging algorithms implemented in ASTRID-H:

- A restricted staging algorithm is used only to assess the feasibility of an existing microlauncher when the mass at lift-off is a known parameter. The complete mathematical formulation has been detailed in [2].
- The optimal staging algorithm is based on Lagrange multipliers. The algorithm optimizes the number of stages to minimize the overall vehicle mass for a given payload mass (m_{PL}) and a specified burnout velocity v_{bo}, [34]. In iDREAM, this staging algorithm can be used both for a new and an existing vehicle. Its full mathematical definition is analyzed in the remaining of this section for a two stages launcher.

The optimal staging algorithm uses two basic concepts, the step mass ($m_{0_{i^{th}stage}}$ [kg]) of the $i^{th} stage$ and the structural ratios, ϵ, to estimate the microlauncher general masses. The step mass is defined as the propellant mass ($m_{p_{i^{th}stage}}$ [kg]) of the stage plus the empty mass ($m_{E_{i^{th}stage}}$ [kg]) of the same stage, neglecting the other stages. The structural ratio, instead, is defined as eq.(1):

$$\epsilon = \frac{m_{E_{i^{th}stage}}}{m_{0_{i^{th}stage}}} \tag{1}$$

The tool will estimate the structural ratios of the different stages by itself. Those ratios are in function of the propellant selected, and their usual value falls in the following intervals:

- Liquid propellant: $0.08 \le \epsilon \le 0.12$;
- Hybrid propellant: $0.10 \le \epsilon \le 0.16$;
- Solid propellant: $0.12 \le \epsilon \le 0.2$.

These two parameters allow the estimation of the empty mass, the propellant mass and the total mass

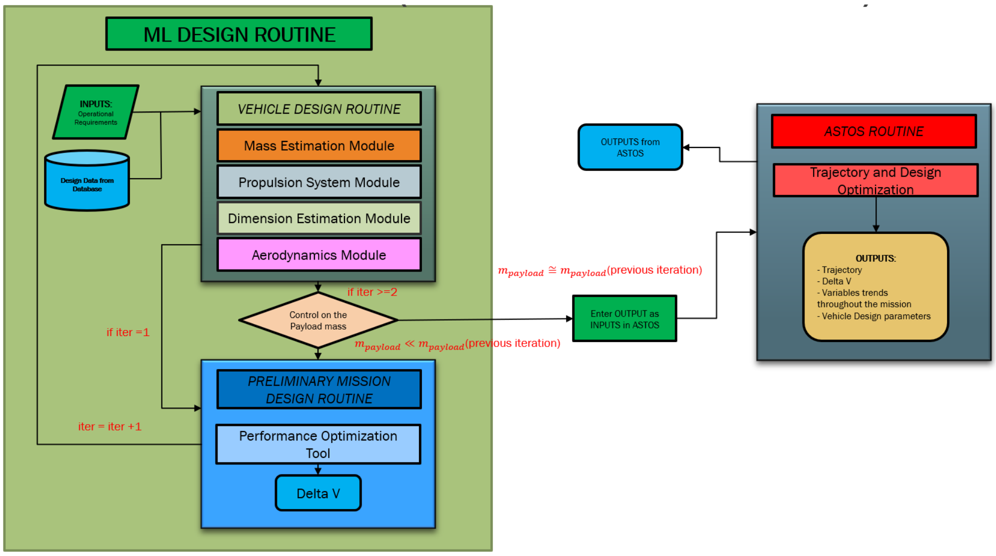


Figure 3: *Design routine for an existing microlauncher using optimal staging.*

(or Maximum Take-Off Mass, Maximum Take-Off Mass (MTOM) [kg]) as described from eq.(2) to (4).

$$m_{0_{i^{th}stage}} = m_{E_{i^{th}stage}} + m_{p_{i^{th}stage}} \tag{2}$$

$$m_{E_{i^{th}stage}} = \epsilon_{i^{th}stage}(m_{E_{i^{th}stage}} + m_{p_{i^{th}stage}}) = \epsilon_{i^{th}stage} m_{0_{i^{th}stage}} \tag{3}$$

$$MTOM = m_0 = \sum m_{0_{i^{th}stage}} + m_{PL} \tag{4}$$

If only two stages are considered, the total mass can be expressed also as in eq.(5):

$$m_0 = m_{0_{stage1}} + m_{0_{stage2}} + m_{PL} \tag{5}$$

This can also be written as eq.(6).

$$\frac{m_0}{m_{PL}} = \frac{m_{0_{stage1}} + m_{0_{stage2}} + m_{PL}}{m_{0_{stage2}} + m_{PL}} \frac{m_{0_{stage2}} + m_{PL}}{m_{PL}} \tag{6}$$

The mass ratios ($n_{i^{th}stage}$) can be expressed as in eq. (7), while the step masses ($m_{0_{i^{th}stage}}$) can be obtained using eq. (8).

$$\begin{cases} n_{stage1} = \frac{m_{0_{stage1}} + m_{0_{stage2}} + m_{PL}}{\epsilon_{stage1} m_{0_{stage1}} + m_{0_{stage2}} + m_{PL}} \\ n_{stage2} = \frac{m_{0_{stage2}} + m_{PL}}{\epsilon_{stage2} m_{0_{stage2}} + m_{PL}} \end{cases} \tag{7}$$

$$\begin{cases} m_{0_{stage1}} = \frac{n_{stage1} - 1}{1 - n_{stage1}\epsilon_{stage1}}(m_{0_{stage1}} + m_{PL}) \\ m_{0_{stage2}} = \frac{n_{stage2} - 1}{1 - n_{stage2}\epsilon_{stage2}} + m_{PL}) \end{cases} \tag{8}$$

Following eq. (9) and eq. (10), it is possible to estimate m_0, by respecting the constraint in eq. (12). Therefore, if m_0 is stationary, then also eq. (11) is stationary.

$$\begin{cases} \frac{m_{0_{stage1}} + m_{0_{stage2}} + m_{PL}}{m_{0_{stage2}} + m_{PL}} = \frac{(1-\epsilon_{stage1})n_{stage1}}{1-\epsilon_{stage1}n_{stage1}} \\ \frac{m_{0_{stage2}} + m_{PL}}{m_{PL}} = \frac{(1-\epsilon_{stage2})n_{stage2}}{1-\epsilon_{stage2}n_{stage2}} \end{cases} \tag{9}$$

$$\frac{m_0}{m_{PL}} = \frac{(1-\epsilon_{stage1})n_{stage1}}{1-\epsilon_{stage1}n_{stage1}} \frac{(1-\epsilon_{stage2})n_{stage2}}{1-\epsilon_{stage2}n_{stage2}} \tag{10}$$

$$\begin{aligned} \ln\left(\frac{m_0}{m_{PL}}\right) = [\ln(1-\epsilon_{stage1}) + \ln n_{stage1} - \\ \ln(1-\epsilon_{stage1}n_{stage1})] + [\ln(1-\epsilon_{stage2}) \\ + \ln n_{stage2} - \ln(1-\epsilon_{stage2}n_{stage2})] \end{aligned} \tag{11}$$

$$\frac{d}{dm_0}\left(\ln \frac{m_0}{m_{PL}}\right) = \frac{1}{m_0} > 0 \tag{12}$$

The burnout velocity, v_{bo}, in this case expressed for a two-stage rocket, can be expressed as a function of the mass ratios and the equivalent velocity, $c = I_{sp}g_0$, as detailed in eq. (13).

$$v_{bo} = v_{bo_{stage1}} + v_{bo_{stage2}} = c_{stage1} \ln n_{stage1} + c_{stage2} \ln n_{stage2} \tag{13}$$

Introducing the Lagrange multiplier η, it's now possible to find the payload ratios λ_{stage1} and λ_{stage2} which guarantees *h*, eq. (14), to be stationary maximizing eq. (11) and hence minimizing m_0 for the desired v_{bo}. By respecting the constraints in eq. (15), the stationarity of *h* is assured.

$$h = [\ln\ (1 - \epsilon_{stage1}) + \ln\ n_{stage1} - \ln\ (1 - \epsilon_{stage1} n_{stage1})] + [\ln\ (1 - \epsilon_{stage2}) + \ln\ n_{stage2} - \ln\ (1 - \epsilon_{stage2} n_{stage2})] + \eta(v_{bo} - c_{stage1} \ln\ n_s tage1 - c_{stage2} \ln\ n_{stage2}) \tag{14}$$

$$\begin{cases} \frac{\delta h}{\delta n_{stage1}} = \frac{1}{n_{stage1}} + \frac{\epsilon_{stage1}}{1 - \epsilon_{stage1} n_{stage1}} - \frac{\eta c_{stage1}}{n_{stage1}} = 0 \\ \frac{\delta h}{\delta n_{stage2}} = \frac{1}{n_{stage2}} + \frac{\epsilon_{stage2}}{1 - \epsilon_{stage2} n_{stage2}} - \frac{\eta c_{stage2}}{n_{stage2}} = 0 \\ \frac{\delta h}{\delta \eta} = v_{bo} - c_{stage1} \ln\ n_{stage1} - c_{stage2} \ln\ n_{stage2} = 0 \end{cases} \tag{15}$$

The eq. (16) held to the estimation of the step masses in eq. (17):

$$\begin{cases} n_{i^{th} stage} = \frac{c_{i^{th} stage} \eta - 1}{c_{i^{th} stage} \epsilon_{i^{th} stage} \eta} \\ \sum_{i=1}^{N} \ln \frac{c_{i^{th} stage \eta - 1}}{c_{i^{th} stage} \epsilon_{stage1} \eta} = v_{bo} \end{cases} \tag{16}$$

$$\begin{cases} m_{0_{stage2}} = \frac{n_{stage2} - 1}{1 - n_{stage2} \epsilon_{stage2}} m_{PL} \\ m_{0_{stage1}} = \frac{n_{stage1} - 1}{1 - n_{stage1} \epsilon_{stage1}} (m_{PL} + m_{0_{stage2}}) \end{cases} \tag{17}$$

Once the step masses have been found, the empty mass and the propellant mass of each stage can be estimated as eq. (18).

$$\begin{cases} m_{E_{i^{th} stage}} = \epsilon_{i^{th} stage} m_{0_{i^{th} stage}} \\ m_{P_{i^{th} stage}} = m_{0_{i^{th} stage}} - m_{E_{i^{th} stage}} \end{cases} \tag{18}$$

To minimize the h function, thus guaranteeing the minimum initial mass, eq. (19), shall be null for i,j=1,….,N (i ≠j).

$$\frac{\delta h^2}{\delta n_{i^{th} stage} \delta n_{j^{th} stage}} \tag{19}$$

For what concerns the v_{bo}, this value is the sum of:

- Δv necessary to reach the desired orbit;
- Gravity loss;
- Drag loss;
- Velocity gain due to Earth's rotation;
- Velocity loss due to steering;
- Margin for unexpected disturbance and accuracy.

The Δv necessary to reach the desired orbit is defined as in eq. (20), where (i) $GM = 398600.4418$ is the Earth's gravitational parameter, (ii) R_{Earth} is the radius of the Earth, (iii) h_0 is the altitude of the launch site, (iv) a is the semimajor axis of the desired orbit ($a = r_{apoapsis} + r_{periapsis}$).

$$\Delta V_{orbit} = \sqrt{GM(\frac{2}{R_{Earth} + h_0} - \frac{1}{a})}[m/s] \tag{20}$$

For what concern the drag and gravity losses, they are set as in eq. (21). This is a first approximation, considering that the gravity losses usually vary between 1000 and 2500 m/s, while the drag losses are between 100 and 700 m/s, [34].

$$\begin{cases} \Delta V_{drag} = 400[m/s] \\ \Delta V_{gravity} = 1750[m/s] \end{cases} \tag{21}$$

The velocity gain due to Earth's rotation is evaluated as detailed in eq. (22).

$$\Delta V_{gain} = \Delta V_{orbit} - \sqrt{(\Delta V_{orbit} \sin Az - V_{phi})^2 + (\Delta V_{orbit} \cos Az)^2} \tag{22}$$

where:

- $V_{phi} = \omega_{Earth} R_{Earth} \cos(latitude)$ is the Earth's speed at the considered altitude.
- $Az = \arcsin(\frac{\cos(inclination)}{\cos(latitude)})$ is the Launch Azimuthal Angle.

For what concerns the velocity loss due to steering ($\Delta V_{steering}$) and the margins for unexpected disturbance and accuracy, they are both set at $100[m/s]$. Both these values are considered as margins to adopt a conservative approach. Finally, the burnout velocity is estimated following eq. (23).

$$\begin{aligned} v_{bo} = \Delta V_{orbit} + \Delta V_{drag} + \Delta V_{gravity} + \\ \Delta V_{steering} + Margin - \Delta V_{gain} \end{aligned} \tag{23}$$

3.1.2 Propulsion system module and dimension estimation module

The propulsion system module allows the estimation of the thrust of the different stages. These values are estimated by using eq. (24) in case the $\frac{T}{W}_{i^{th} stage}$ is known. Otherwise, the tool will estimate these values thanks to the regression formula detailed in [35].

$$T_{i^{th} stage} = \frac{T}{W}_{i^{th} stage} m_{0_{i^{th} stage}} g_0 [N] \tag{24}$$

The methodology supports the design of micro-launchers using liquid propellant, solid propellant, or hybrid propellant. In the tool, there are some preloaded propellants' characteristics for the most commonly used combinations [36] such as: Oxygen – Kerosene; Oxygen – Methane; Oxygen – Hydrogen; Oxygen – Liquified Petroleum Gas (LPG) (Liquified Petroleum Gas); H2O2 – Hydroxyl-Terminated Polybutadiene (HTPB) (Oxidizer: Hydrogen Peroxide, Fuel: Hydroxyl-Terminated Polybutadiene); Hydrazine; HTPB. All the propellants are characterized in terms of mixture ratio (in case of bi-propellant), vacuum I_{sp}, density (fuel and oxidizer density in case of bi-propellant and propellant density in case of mono-propellant). The user can introduce new propellants types, indicating the previous mentioned characteristics.

For liquid rocket engines, Liquid Rocket Engines (LRE), the lengths of the different stages is preliminary evaluated following eq. (25) [37].

$$L_{LRE} = L_{engine} + L_{tanks} [m] \tag{25}$$

If the geometrical characteristics of the engine are unknown, it is possible to estimate the length of the engine by using eq. (26)[38].

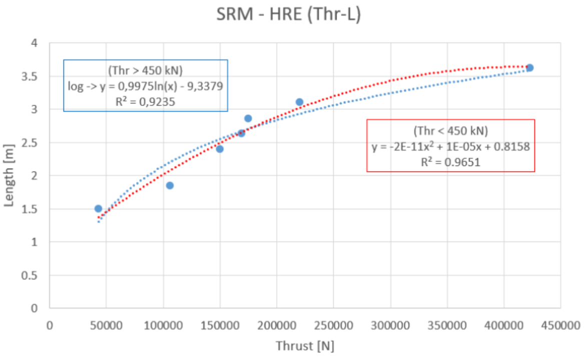


Figure 4: *SRM - glshre Regression law Thrust [N]-Length [m].*

$$\begin{cases} L_{engine_{TP}} = 0.88 T^{0.255} n_{engine}^{-0.4} (\frac{A_e}{A_t})^{0.055} \\ L_{engine_{PF}} = 1.4921 \ln(T) - 13.179 \end{cases} \tag{26}$$

Where: (i) T is the stage thrust [N], (ii) n_{egine} is the number of engines, (iii) $\frac{A_e}{A_t}$ is the expansion ratio, (vi) TP stands for "turbopump cycle", and (v) PF stands for pressure-fed cycle.

For what concerns the tanks, they are dimensioned as cylindrical bodies with spherical end caps or as spherical tanks. The thickness is estimated as in eq. (27) [39], where (i) sf is a safety factor set to two, (ii) p_{tank} is the tank pressure, (iii) D_{rocket} is the rocket diameter, and (iv) σ is the stress material.

$$\tau_{tank} = sf \frac{p_{tank} 2 D_{rocket}}{2\sigma} \tag{27}$$

If the user analyses a solid rocket motor, the engine length is estimated as in eq. (28) if the geometrical characteristics of the nozzle are known, otherwise it can be estimated using the regression formulas shown in Figure 4.

$$L_{engine} = L_{conv} + L_{div} = L_{nozzle} \tag{28}$$

Where:

- $L_{conv} = \frac{D_{case} - D_{throat}}{2 \tan \beta} [m]$
- $L_{div} = K \frac{D_{Exit} - D_{throat}}{2 \tan \theta}$

The nozzle mass is estimated by using the Mass Estimation Relationship (MER) detailed in [40]. While, the tanks are assumed cylindrical and they are estimated as detail in the liquid rocket stage paragraph.

The hybrid rocket engine is sized as the solid rocket one. However, its tanks are evaluated as for the liquid rocket engine for what concerns the oxidizer and as for the solid rocket motors for the fuel, [41].

Finally, the microlauncher fairing is sized as in eq. (29).

$$\begin{cases} L_{fairing} = 0.5(\frac{L}{R})_{ogive} D_{PL} + L_{PL} + 0.15 D_{PL} \\ m_{fairing} = 4.95 S_{nose}^{1.15} \end{cases} \tag{29}$$

Where: (i) $(\frac{L}{R})_{ogive}$ is the nose ratio, (ii) D_{PL} is the payload diameter, (iii) L_{PL} is the payload length, and (iv) S_{nose} is the fairing surface.

The fairing sizing completes the preliminary dimension and propulsion system estimation of microlaunchers inside iDREAM.

The final total length of the rocket is calculated as in eq. (30).

$$L_{total} = \sum_{i=1}^{N} L_{i^{th}stage} + L_{fairing} \tag{30}$$

Where

- $L_{i^{th}stage} = L_{engine_{i^{th}stage}} + L_{tank_{i^{th}stage}} + L_{int_{i^{th}stage}}$

3.1.3 Preliminary mission design routine

The preliminary mission design routine is used in the total mass minimization routine to estimate a more accurate ΔV than the tabulated ones available in literature, as well as drag and gravity losses. The algorithm relies on a two-dimensional trajectory of which the equations of motion are defined as in eq.(31), [42] [43].

$$\begin{cases} dr = v_{rad}[m/s] \\ d\theta = \frac{v_{tan}}{r}[m/s] \\ dv_{rad} = \frac{v_{tan}^2}{r} + \frac{\delta Thr}{m}\sin\alpha - \frac{GM}{r^2} \\ \quad -\frac{1}{2}\rho CD\sqrt{v_{rad}^2 + v_{tan}^2} A v_{rad}[m/s^2] \\ dv_{tan} = \frac{v_{tan}v_{rad}}{r} + \frac{\delta Thr}{m}\cos\alpha \\ \quad -\frac{1}{2}\rho CD\sqrt{v_{rad}^2 + v_{tan}^2} A v_{tan}[m/s^2] \\ dm = -\frac{\delta Thr}{g_0 I_{sp}}[kg/s] \\ d\Delta V = I_{sp} g_0 \ln(\frac{m}{m+dm})[m/s^2] \\ d\Delta V_{drag} = \frac{Drag}{m}[m/s^2] \\ d\Delta V_{gravity} = \frac{g_0}{r/R_{Earth}}\sin\gamma[m/s^2] \end{cases} \tag{31}$$

Where: (i) r is the distance between the microlauncher and the centre of the main body (Earth), (ii) θ is the angle of the Launcher with respect to a reference point of the surface (starting point), (iii) GM is the standard gravitational parameter of the Earth, (iv) m is the total mass of the system, (v) Thr is the thrust provided by the engines, (vi) g_0 is the standard gravity acceleration at sea level, (vii) Cd is the drag coefficient, (viii) A is the cross-sectional area, (ix) $\gamma = \arccos\frac{v_{tan}}{\sqrt{v_{tan}^2+v_{rad}^2}}$ is the flight path angle.

Those equations are used in minimization optimization algorithm that controls:

- Throttle: δ $[\delta_{min}; 1]$
- Thrust angle: α $[-\frac{\pi}{2}; \frac{\pi}{2}]$
- Fuel fraction: f_f $[0; 1]$
- Coast time: t_{coast} $[0; 5000]$

Imposing the objective function defined in (32).

$$\begin{cases} v_{rad} = 0[m/s] \\ v_{tan} = \frac{\sqrt{GM}}{r_{target}}[m/s] \\ r_{reached} - r_{target} = 0[m/s] \end{cases} \tag{32}$$

3.2 Technological Roadmap

Looking at Figure 2, it is possible to see that the TRIS methodology starts from an in-depth *analysis of the Stakeholders* involved in the process. This step is essential to identify from the beginning of the roadmapping activities all the entities involved in the process, specifying their role(s) and predicting their impact on the final decision. According to systems engineering best practices, all the actors shall be categorized depending on their role (sponsors, operators, end-users and customers) and characterized according to their main areas of interest in the analysis (final mission needs, political needs, general public needs, economic needs, scientific needs, or technological needs). Depending on the category and area of interest to which each stakeholder belongs, it is possible to predict each actor's influence and interest. Depending on the influence and interest of each stakeholder, their needs shall be weighted appropriately, thus allowing to move from qualitative analysis to a quantitative estimation. To complete this transition, it is also necessary to translate the needs expressed by the stakeholders into measurable criteria to be used during the *prioritization study*.

The second step of this methodology consists of the *definition and characterization of lists of elements* for each roadmap pillar:

- Operational capabilities (Operational Capability (OC)s), defined as a high-level function responding to a mission statement (or, more generally, to a research study objective).
- Building blocks (Building Block (BB)s), defined as physical elements that may include several technologies combined together to achieve certain functions (OCs).
- Mission concepts (Mission Concepts (MC)), defined through a mission statement and made up of BBs, to implement several OCs and use certain technologies.
- Technology area (Technology Area (TA)), defined as a set of technologies that accomplish one or more OCs and usually is subject to further sub-categorizations (i.e. Technology Subject and Technology)

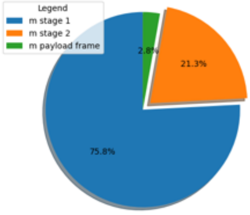
Again, the availability of a well-structured database helps define and characterize these lists. In this concept, specific attention has been given to the definition of the list of technologies and preliminary estimation of the cost and time resources associated with each TRL transit. Eventually, these values are used in the *prioritization study*, where the list of technology and activities are ordered to mirror the needs expressed by the stakeholders at the beginning of the process. To complete the *planning definition*, the ordered list of MCs has to be properly distributed on a timeline. For this purpose, a new semi-empirical model for time resource allocation is proposed to improve the planning definition algorithm, thus increasing the accuracy of time allocation. The *results evaluation* step can be considered a synthesis of the overall roadmapping activities carried out in the previous steps. This step supports the analysis of different out-of-nominal scenarios and sensitivity analysis to understand the impact of stakeholders' expectations on the final roadmap. This also allows performing a risk analysis, associating each technically viable roadmap to a level of risk depending on the foreseeable difficulties in reaching the TRL target. Likewise, the results of different technology roadmaps (either as mission or product) can be compared based on the expected revenues, which can be expressed as stakeholders' criteria, thus analyzing the impact of stakeholders' expectations on the final roadmap.

4. Validation Study: The Electron

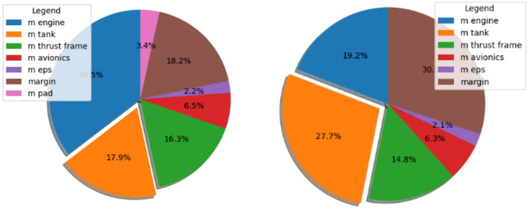
The previously introduced methodology has been validated against the design of the Electron [44]. The Electron launch vehicle, entirely designed and manufactured by Rocket Lab, is one of the first micro-launchers ever launched. It combines the latest manufacturing technologies with the capability of multiple launch ranges in a domestic launch site, the Mahia launch complex. Its performances allow Electron to be one of the best solutions for quickly launching small satellites' constellations. Electron exists both as a two-stage and a three-stage configuration. The two-stage architecture is analysed in this validation study case.

The design assessment of iDREAM needs as inputs the mission data detailed in Table 1. The listed data are available on the developer, Rocket Lab, site or from literature [44].

The design routine outputs are listed in Table 2. The percentage of the difference between the values estimated by iDREAM and the values in [44] are less than 10%. This value is considered an acceptable margin for preliminary design tools [13]. Figure 5 details the mass breakdown for the overall vehicle and the single stages as estimated by



(a) Mass breakdown.



(b) 1^{st}_{stage} mass breakdown.

(c) 2^{nd}_{stage} mass breakdown.

Figure 5: *Mass breakdowns.*

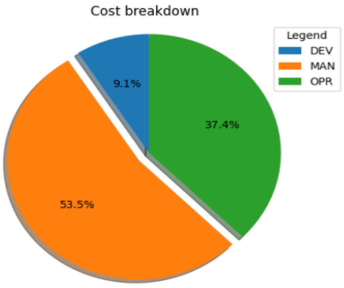


Figure 6: *HyCost Cost Breakdown for Electron.*

Parameter	**Value**	**Unit**
Target Orbit	300.0	km
Orbital Inclination	45	deg
Launch site selection	Mahia, New Zealand	
Number of stages	2	
Nominal payload mass	200.0	kg
Rocket diameters	1.2	m
1^{st}_{Stage} Thrust over weight	2	
2^{nd}_{Stage} Thrust over weight	0.95	
Maximum Take Off Mass	12.5	t
Total Length	18.0	m
1^{st}_{Stage} Propellant	LOx/RP1	
2^{nd}_{Stage} Propellant	LOx/RP1	
1^{st}_{Stage} Number of engines	9	
2^{nd}_{Stage} Number of engines	1	

Table 1: *Vehicle design inputs.*

iDREAM.

ASTRID-H results are used as inputs to run the cost estimation routine, HyCost. The LCC assessment can be further refined if programmatic data like the number of launches per year and the total number of units to be produced are introduced into the routine. The cost estimation provides values for the development, manufacturing, and operating costs, as well as the cost and price per flight (considering a profit margin typical for commercial applications), as shown in 6 and detailed in Table 3. The results are very close to the reference cost values, providing a good case study for the tool validation, Table 4. The subsystem costs are grouped into technology categories to assess the technology cost at completion (CaC) used for the roadmap routine.

Finally, to generate the technology roadmap, some general programmatic inputs has been set:

- Start Date: 01-01-2014 (Electron launch vehicle)
- End Date: 11-11-2018 (first Electron Mission - IT'S BUSINESS TIME)
- Target TRL: 9

[45] has been used as main reference to define a likely-to-be stakeholders' analysis, the output of this analysis is detailed in Table 5, where:

- OP = Operator

Parameter	**iDREAM Existing vehicle**	**Electron [44]**	**Percentage differences [%]**
Payload Mass [kg]	268.59	280.00	-4.08
Payload Diameter [m]	1.07	1.08	-0.93
MTOM [t]	12.49	12.5	-0.08
1^{st}_{Stage} Inert Mass [t]	0.89	0.90	-1.11
2^{nd}_{Stage} Inert Mass [t]	0.19	0.20	-5.00
Fairing mass [kg]	44.04	44.00	0.09
Fairing Length [m]	2.57	2.40	7.08
Total Length [m]	18.00	18.00	0.00
1^{st}_{Stage} Thrust [kN]	244.97	224.30	9.22
2^{nd}_{Stage} Thrust [kN]	27.79	25.80	7.71
1^{st}_{Stage} engine mass [kg]	35.58	35.00	1.66
2^{nd}_{Stage} engine mass [kg]	38.15	35.00	9.00

Table 2: *Vehicle design outputs.*

Parameter	**Value**	**Unit**
T1-equivalent	14073	$k€$
Development	71479	$k€$
Dev per unit	1429.57	$k€$
Manufacturing	423508	$k€$
MAN per unit	8470.16	$k€$
Operating	6144	$k€$
Cost per flight	16044	$k€$
Price per flight	17327	$k€$
Specific price	52.16	$k€/kg$

Table 3: *Cost Estimation outputs.*

- E-U = End-User
- C = Customer
- SP = Sponsor
- KE = Keep–Engaged
- MON = Monitor
- KS = Keep-Satisfied
- KI = keep-Informed
- CaC = Cost at Completion
- MS = Missions
- AC = Activities
- AS = Ascending
- DS = Descending

	Price per flight [$k€$]	**Specific price** [$k€/kg$]
Electron	16200	54
iDREAM	17327	52.16
Percentage differences [%]	6.96	-3.70

Table 4: *Cost Estimation outputs.*

Stakeholder	**Role**	**Impact**	**Criterion**	**Prior order**
Rocket Lab	OP	KE	Current TRL	AS
Rocket Lab	OP	KE	CaC	DS
Rocket Lab	OP	KE	n° MS linked	AS
Rocket Lab	OP	KE	n° AC linked	AS
Rocket Lab	OP	KE	n° BBs linked	AS
Rocket Lab	OP	KE	n° OCs linked	AS
PoliTo	E-U	MON	Current TRL	AS
PoliTo	E-U	MON	CaC	DS
NASA	C	KE	CaC	DS
NASA	C	KE	n° MS linked	AS
U.S. Govt	SP	KS	n° MS linked	AS
DARPA	SP	KI	CaC	DS
DARPA	SP	KI	n° MS linked	AS
ESA	OP	KI	CaC	DS
ESA	OP	KI	Current TRL	AS

Table 5: *Stakeholder analysis.*

For the assessment in this paper, the technologies relative to the engine have been selected as enabling technologies. The output of TRIS for the technologies priotization is summarized in Table 6 and Figure 7. Figure 8 presents a gantt-like chart of the technologies planning.

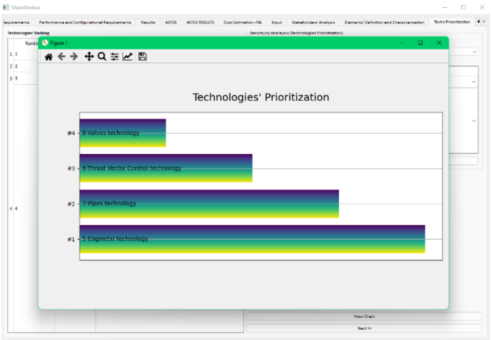


Figure 7: *Technologies prioritization in iDREAM GUI.*

Ranking	Technology name	Current TRL
1	Engine(s) technology	5
2	Thrust Vector Control technology	6
3	Pipes technology	6
4	Valves technology	6

Table 6: *Stakeholder analysis.*

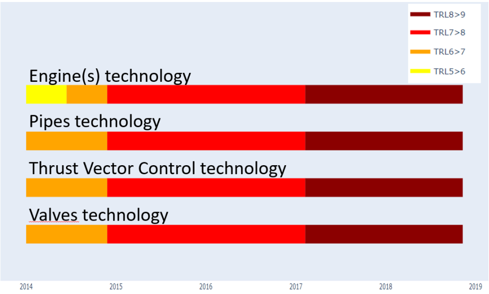


Figure 8: *Technologies planning.*

5. Conclusions and Future Work

This paper described the methodology developed at Politecnico di Torino to support the development of a range of space systems. The methodology is actualized in the form of an integrated software called iDREAM with the capabilities of providing a preliminary design of the studied system, estimating the overall life-cycle cost of the designed system, and supporting the evaluation of technology roadmaps. These three capabilities are realized thanks to three software, ASTRID-H, HyCost, and TRIS integrated in iDREAM. The three can be used as stand-alone modules as well. The paper provides an overview of those capabilities detailing as well the mathematical apparatus behind the iDREAM evaluations. The effectiveness of iDREAM is then demonstrated with its application to size a microlauncher with a mission profile and orbit-delivered payload mass similar to the Rocket Lab Electron. The overall design methodology can provide a complete design of a system similar to the Electron, maintaining the errors between masses and dimensions at less than 10% (in line with the expectations of percentual error of a conceptual design phase).

Future works will focus on extending the tool, iDREAM capabilities to the design and life-cost assessment of diverse space systems. Moreover, the PoliTO team would keep refining the HyDat database to include more proven, ready-to-fly and already-flown designs to improve the overall design estimation.

Acronyms

ASI	Italian Space Agency
ASTOS	Analysis, Simulation and Trajectory Optimization Software for Space Applications
ASTRID-H	Aerospace on-board Systems sizing and Trade-off analysis in Initial Design
BB	Building Block
CER	Cost Estimation Relationships
ESA	European Space Agency
GSTP	General Support Technology Programme
GUI	Graphical User Interface
HTPB	Hydroxyl-Terminated Polybutadiene
iDREAM	Integrated Design Roadmapping and Engineering stand-Alone Module for high-speed vehicle
LCC	Life-Cycle-Cost
LL	Lunar Lander
LPG	Liquified Petroleum Gas
LRE	Liquid Rocket Engines
MC	Mission Concepts
MER	Mass Estimation Relationship
ML	Microlaunchers
MTOM	Maximum Take-Off Mass
OC	Operational Capability
PoliTO	Politecnico di Torino
SQL	Structured Query Language
TA	Technology Area
TRIS	Technology Roadmapping Strategy
TRL	Technology Readiness Level

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