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

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Abstract. For the rapid prototyping of a flight engineering vehicle, data from various building blocks and the required engineering tools for designing critical subsystems are crucial elements. In this context, Politecnico di Torino developed an integrated methodology toolset capable of speeding up the design and validation of various space transportation systems, with a focus on microlaunchers and human landing systems. This research was carried out under the direction of the European Space Agency (ESA).

iDREAM methodology

This methodology not only enables the conceptual design of the new vehicle, but also completes it with an exhaustive analysis of the solution's viability from an economic and technical standpoint. As a result, this methodology can be utilized for three primary purposes, each of which can be used independently or together with automatic connections, as schematically represented in Figure 1:

1. Design and related mission analysis
2. Life Cycle Cost (LCC) assessment
3. Technology roadmap

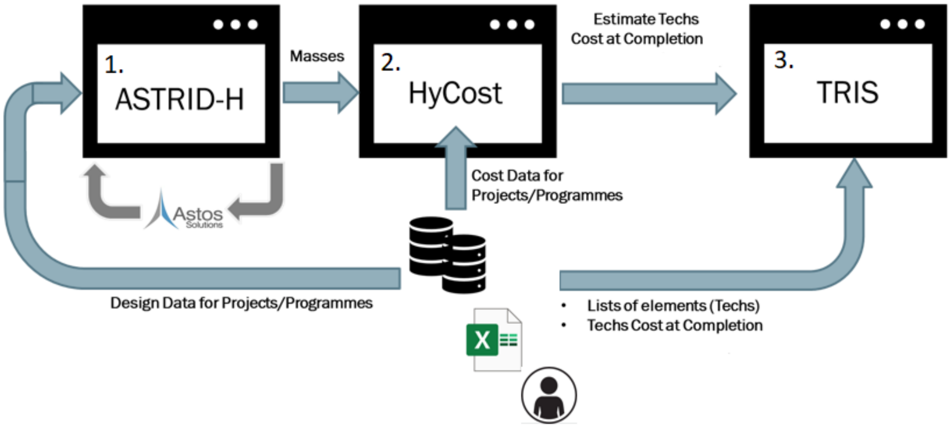

Figure 1: iDREAM path.

ASTRID-H

The first iDREAM capability was exploited using ASTRID-H, as shown in Figure 1. The main purpose of this tool is to support the rapid prototyping of Micro-Launcher (ML) and Human Landing System (HLS).

Building on extensive experience in developing methodologies to support the conceptual and preliminary design of complex aerospace vehicles and integrated subsystems, and leveraging the proprietary software tool ASTRID, Politecnico di Torino has improved ASTRID-H, a methodology and tool that was originally designed for high-speed vehicle applications.

Leveraging on the European Space Agency's interests, two different case studies have been identified: (i) MicroLauncher and (ii) Human Landing System.

The increasing interest in launching small satellites and the limitations associated with launching such payloads have led to the development of MicroLaunchers (ML) as a potential solution to make such missions more affordable. In this context, PoliTO has devised a two-fold methodology. First, it involves using two mass estimation algorithms (Restricted and Optimal Staging) to validate an existing vehicle design, which leads to a redesign and a deeper exploration of subsystems and missions. The second part involves creating a new ML and its associated mission based on a set of high-level requirements. To ensure the accuracy and viability of the design, there is a direct connection with the commercial mission analysis software ASTOS, which enables iterative improvement of the design and mission by working in tandem with the vehicle design and mission analysis routines. Overall, this approach facilitates the development of an optimized Micro-Launcher or verification of the design and mission of an existing one.

The second scenario pertains to a Lunar Lander, also known as a Human Landing System, which is an essential component for exploring the Moon, as outlined in the Global Exploration Roadmap 2018 [1] and Global Exploration Roadmap Supplement – Lunar Surface Exploration Scenario Update 2020 [2] by the International Space Exploration Coordination Group (ISECG). PoliTO has developed a methodology to aid in the conceptual design of a Human Landing System (HLS) for future lunar missions involving astronauts. Depending on the information provided by the Agency, the HLS is intended to be a single-stage vehicle and will be responsible for transportation between the Moon's surface and the Lunar Orbital Platform-Gateway (LOP-G). Based on the requirements specified by the Agency, the Human Landing System (HLS) must be reusable up to five times, host four astronauts, and remain on the moon's surface for three moon nights. With the primary objective of the design process established, the PoliTO team developed a design methodology involving a preparatory conceptual design activity in ASTRID-H and a mission analysis using the commercial software ASTOS. However, the design approach for the HLS differs from that of the MicroLauncher, as it follows a bottom-up approach starting with subsystem design and proceeding to vehicle design. Once the mass, power, and volume budgets of the spacecraft are estimated, they can be utilized as inputs to initialize ASTOS and supplement the design with a proper mission analysis.

HyCost

The second component depicted in Figure 1, is the economic feasibility module.

Benefitting from the long-time experience in developing methodologies to support the assessment of the Life Cycle Cost (LCC) of complex aerospace vehicles, Politecnico di Torino upgraded its proprietary tool HyCost to support a wide range of high-speed vehicles [3] [4] [5], using a different approach for ML and HLS.

For what concern the first case study, the MicroLaunchers (ML), various cost estimation methodologies were evaluated, and those proposed by Drenthe [6] and ESA [7] were chosen.

This methodology, which is based on T1 equivalent units and linear factors applied at the subsystem and equipment levels, is focused on small commercial launch vehicles. This method was chosen as the best fit because it provides more flexibility when taking into account new technologies, and subsystem-level considerations give the estimates a high degree of accuracy. The estimates can also be easily refined when new data and updates regarding these innovative launchers are released.

The second case study undertaken by Politecnico di Torino focused on assessing the life cycle cost (LCC) of Human Landing Systems (HLS). In order to perform this analysis, a thorough review of the relevant literature on cost-estimating methodologies for space systems and programs was conducted, which identified three primary strategies: (i) Analogy, (ii) Parametric, and (iii) Engineering build-up [8]. Following this, various cost models and tools were evaluated, including the Advanced Missions Cost Model (AMCM) and the Unmanned Space Vehicle Cost Model (USCM).

Based on the specific requirements of this project and the available data, the analogy cost-estimating methodology was determined to be the most suitable. This approach was deemed appropriate due to the early design phase of the system and the limited availability of consistent data on similar systems. Other available models were used for comparison and validation purposes.

TRIS

The third module, TRIS, produces a technology roadmap that assesses the technology readiness and risk for each technology, as well as identifies future activities, missions, and necessary developments. Such technology roadmapping methodologies are designed to pinpoint the essential technologies and activities required for technology development, operational capabilities, and building blocks based on pre-determined performance targets [9].

The third module, TRIS, generates a technology roadmap that estimates the technology readiness and risk assessments for each technology, along with necessary future works, activities, and missions.

Technology roadmapping methodologies are meant to identify the enabling technologies and activities needed for technology development, operational capabilities, and building blocks based on predefined performance targets [9].

Current roadmap activities aim to analyze complex systems and generate an incremental and sustainable technology development plan, or technological roadmap, that must be periodically reviewed by experts involved in strategic decisions. The TRIS methodology developed at Politecnico di Torino is complementary to other approaches found in the literature [10], [11], [12], [13], [14], [15] and generates technology roadmaps capable of supporting strategic decisions in combination with brainstorming sessions with experts' opinions By utilizing a rational, objective, and traceable methodology, TRIS defines gradual paths of technology maturation for new missions, products, or capabilities. TRIS enhances traditional techniques by highlighting feasible incremental pathways to the ultimate goal, by utilizing shared System Engineering tools and processes [16] [17] and purpose-built tools. As intended in TRIS, a technology roadmap is the product of various activities that identify, prioritize, select, and merge elements that fall under the technology roadmap pillars (Operational Capabilities, Technologies, Building Blocks, and Mission Concepts).

Looking at TRIS in detail, the methodology consists of five main steps: Stakeholders' Analysis, Elements' Definition, Prioritization Studies, Planning Definition and Results Evaluation, as detailed in Figure 2:

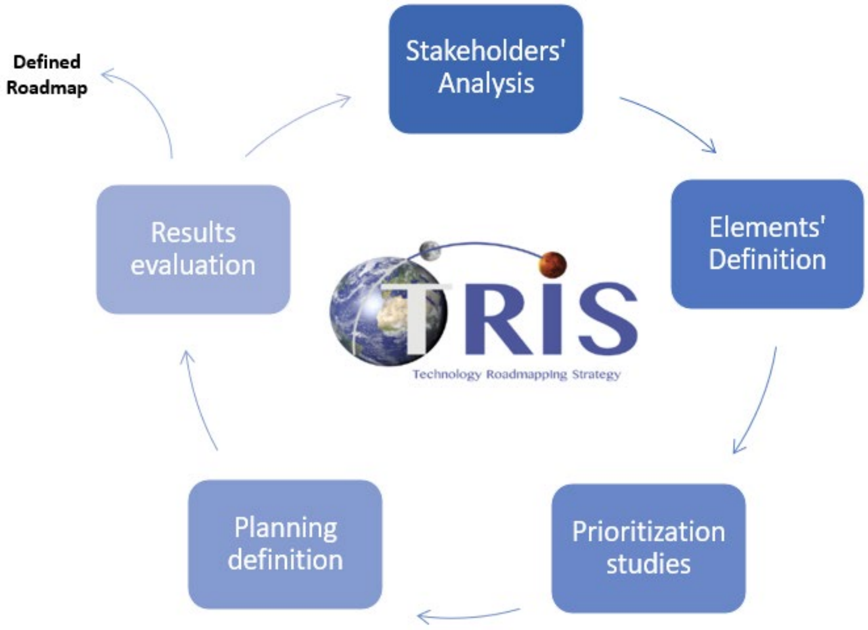

Figure 2: TRIS methodology.

The process begins with the Stakeholders' Analysis, which plays a crucial role in identifying all the involved parties, determining their roles (Sponsors, Operators, End-users and Customers) and assessing their impact (keep engaged, keep informed, keep satisfied, and monitor) on the final decision. Depending on the category and area of interest, the influence and interest of each actor can be predicted, and their level of influence and interest can be used as a weighting factor for the needs they express.

The second step involves defining and characterizing the various elements or pillars that constitute a roadmap. These elements include (i) Operational Capability (OC), which refers to a high-level function that satisfies a mission statement or research objectives; (ii) Technology Area (TA), which refers to a set of technologies that accomplish one or more OCs and is often further subcategorized into Technology Subject and Technology; (iii) Building Block (BB), which is a physical element that may include several technologies combined to achieve specific functions (OCs); and (iv) Mission Concept (MC), which is defined by a mission statement and comprises BBs to implement several OCs and make use of certain technologies.

The third step of the process entailed a trade-off analysis-based prioritization. In this phase, all criteria derived from the Stakeholders' Analysis can function as figures of merit that contribute to the final ranking of technologies based on their corresponding stakeholder influence and interest. Using the information gathered during the Elements' Definition phase, a list of Operational Capabilities (OCs) and Mission Concepts (MCs) associated with each identified technology was created to facilitate the required Technology Readiness Level (TRL) Transit, as specified by the ESA Standards.

The fourth step in the roadmap process involves Planning Definition, which entails appropriately scheduling the list of Mission Concepts (MCs) within a suitable timeline. To achieve this, a semi-empirical model was developed by conducting a comprehensive literature review of Space Exploration data, which employs a specific time-allocation breakdown. This breakdown is used to determine an initial development timeline for each technology, which is then further refined with the actual list of Activities (ACs) and Mission Concepts (MCs) required to meet each Technology Readiness Level (TRL) Transit, as per the standards set by the European Space Agency (ESA).

In cases where a specific AC or MC is associated with multiple technologies, its starting date is fixed only after all relevant technologies have attained the minimum TRL required by the AC/MC. This step facilitates the definition of the final timeline for each technology, and by merging it with the ordered and linked list of ACs/MCs, the final plan is generated, along with the incremental path for each technology's maturation. The expected graphical output includes two Gantt Charts: one displaying the time and budget allocation for each technology on TRL Transits, along with TRL Milestones, and the other focusing on the ordered list of ACs/MCs along the same timeline. This dual visualization is feasible due to the well-established relationship between technologies and ACs/MCs.

During the Results Evaluation step, the roadmapping activities carried out in the previous steps are integrated and risk analysis is performed to assess the level of risk associated with each feasible roadmap, taking into account the anticipated challenges in achieving the target Technology Readiness Level (TRL). The risk analysis aids in exploring different out-of-nominal scenarios and conducting a sensitivity analysis to assess the influence of stakeholders' expectations on the final roadmap.

Database connection

In addition to the aforementioned capabilities, iDREAM rely on two distinct MySQL databases, which are specifically designed to support the other modules of the toolset. This support is made possible by a Database Management Library that ensures a unified connection between the input and output of data. The two databases used were named TREX and HyDat. TREX, the first database, is exclusive to the European Space Agency and was utilized in the Human Landing System case study. The second database, HyDat, was developed internally by Politecnico di Torino and was originally intended for use in the design of hypersonic and reusable vehicles for space access. Subsequently, it was adapted to facilitate the MicroLauncher case study and was also employed in another contract between PoliTo and ESA. Eventually, this database has been modified to accommodate a wide range of vehicles, including the Human Landing System.

Case study: MicroLauncher

The case study presented here is based on Rocket Lab ML Electron [18]. Completely designed and produced by Rocket Lab, the Electron launch vehicle is one of the first ML ever launched.

Table 1 details the main results achieved by comparing the iDREAM ASTRID-H tool with the actual values of the Electron ML, while Table 2 lists the outcomes of the cost-estimating tool. Errors under 10% were obtained, which is entirely consistent with the conceptual design process.

Table 1: Results of iDREAM ASTRID-H routine compared with Electron actual values.

Global Input Variable Name	Electron [iDREAM]	Electron	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
1st Stage Inert Mass [t]	0.89	0.90	-1.11
2nd 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
1st Stage Thrust [kN]	244.97	224.30	9.22

2nd Stage Thrust [kN]	27.79	25.8	7.71
1st Stage engine mass [kg]	35.58	35.00	1.66
2nd Stage engine mass [kg]	38.15	35.00	9.00

Table 2: Results of iDREAM HyCost routine compared with Electron actual values.

	Price per Flight [k€]	Specific Cost [k€/kg]
Electron	16200	54
Electron [iDREAM]	17327	55
Percentage differences [%]	6.96	-3.70

Case study: Human Landing System

This article presents a case study based on the ESAS LSAM spacecraft [19] [20], which is considered one of the most comprehensive projects in lunar surface access. The spacecraft, developed by the ESAS team with NASA's assistance, features state-of-the-art manufacturing technologies and multi-lunar mission capabilities. Although the ESAS LSAM is a 2-stage spacecraft, for this analysis, the lander is considered a single stage that encompasses both the ascent and descent modules, with a focus on the descent mission phases. The ascent module is treated as payload mass in this study. However, due to this approximation, some percentage differences exceed 10% when comparing the results obtained using the iDREAM ASTRID-H methodology with the actual values of the ESAS LSAM, as shown in Table 3. These discrepancies may be attributed to the lack of data about the LSAM subsystem [19] [20] [21].

Table 3: Results of iDREAM ASTRID-H routine compared with ESAS LSAM actual values.

Global Input Variable Name	ESAS LSAM [iDREAM]	ESAS LSAM [15]	Percentage differences [%]
ECLSS Mass [kg]	1177	1312	-10.29
Avionics mass[kg]	678	655	3.51
Propulsion mass [kg]	3810	3905	-2.43
Structure mass [kg]	2965	2841	4.36
EPS mass [kg]	1310	1246	5.14
Other mass [kg]	1155	1022	13.01
Dry mass [kg]	10421.3	11264	-7.48
Wet mass [kg]	40163	45861.6	-12.43
Fuel mass [kg]	25580.7	29820	-14.22

The results achieved by ASTRID-H are used as inputs to run Cost Estimation Routine (HyCost) and to obtain the outcomes detailed in Table 4.

Table 4: Results of iDREAM HyCost routine compared with ESAS LSAM actual values.

	Development and Production Cost [M€]
ESAS LSAM [13]	5500
ESAS LSAM [iDREAM]	5993
Percentage differences	8.23 %

Conclusion and Future works

Although the results obtained in this study were in line with the expectations, future work will employ a distinct approach that capitalizes on the significant advancements made possible by AI-based tools. Specifically, a design assistant leveraging a Knowledge Graph (KG) will be developed to evaluate the feasibility of various mission architectures. The KG, which is a semantic network that represents entities and their relationships, will be utilized to collect explicit and implicit knowledge and serve as the backbone of this new methodology. This approach will enhance the design process by enabling quick and effortless access to past design choices and exploring new design alternatives.

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