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HUMAN LUNAR LANDER SYSTEM DESIGN, COST ESTIMATION AND TECHNOLOGY ROADMAPS (GSTP I-DREAM PROJECT)

D. Chirulli, G.Narducci, G. Governale, N. Viola, J. Rimani, R. Fusaro, D. Ferretto*
Mechanical and Aerospace Engineering Department, Politecnico di Torino

S. Chiusano and A. Fiori
Computer Sciences Department, Politecnico di Torino

O. Cohen and E-M Dupuy
European Space Research and Technology Centre(ESTEC), European Space Agency (ESA), The Netherlands

**corresponding author: donato.chirulli@studenti.polito.it*

ABSTRACT

This paper describes the methodology developed at Politecnico di Torino to support the European Space Agency in the Human Lunar Landing System design activity and to complement the traditional conceptual design with a multidisciplinary set of analyses which includes a thorough assessment of the economic and technological viability of the solution. The paper briefly describes the logic laying behind each of these analyses and it shows the results of the validation of the integrated design methodology, called iDREAM, with an already existing case study, the *Exploration Systems Architecture Study-Lunar Surface Access Module* spacecraft (ESAS-LSAM). The results are satisfactory and reveals errors lower than 10% in average, perfectly in line with the expectations of a conceptual design phase.

Index Terms— Human Lunar Lander, vehicle and mission design, Life-Cycle Cost Assessment, Technology Roadmap

1. INTRODUCTION

The interest in the lunar exploration missions with human involved has recently been rediscovered [1]. In recent years, the moon has become the target of upcoming space programs. Earth's natural satellite is represented as the starting point for the next phase of human space exploration. In this scenario, the need to design and develop new concepts of Human Landing System (HLS), has arisen, aiming at aimed at enhancing the affordability in lunar mission.

In this very challenging context, thanks to Italian GSTP funds, Politecnico di Torino is supporting the European Space Agency in developing an integrated multidisciplinary methodology to speed-up the design and validation of new HLSs and related missions. The methodology developed at Politecnico di Torino allows to complement the conceptual design of the new vehicle 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 thanks to a parametric model, based on Cost Estimation Relationships (CERs) having vehicle design variables and performance as main drivers. Complementary, the technological viability of the solution is checked not only through a Technology Readiness Level (TRL) assessment, but thanks to the generation of a technology roadmap, i.e. an incremental path leading to the maturation of the enabling technologies, containing indications on the time and budget resources to be allocated.

This paper specifically aims at describing this methodology developed and implemented by Politecnico di Torino in an integrated software application called iDREAM.

After this brief introduction, iDREAM methodology is in depth-investigated in Section and complemented with some insights on the software tool implementation. Then, Section 3 collects the main results of the validation of the methodology against an already existing HLS project. Eventually, main conclusions are drawn and ideas for future applications and further developments of the methodology and software tool are reported.

2. I-DREAM METHODOLOGY TO SUPPORT HUMAN LANDING SYSTEM MULTIDISCIPLINARY DESIGN

i-DREAM is an integrated multidisciplinary methodology developed at Politecnico di Torino to speed-up the design and validation of new HLSs and related missions. The methodology allows to complement the conceptual design of the new vehicle with a thorough assessment of the economic and technological feasibility of the solution. Therefore, i-DREAM methodology can be described as an integrated analysis framework encompassing the three main capabilities reported hereafter:

1. HLS design and related mission analysis;
2. HLS LCC assessment
3. HLS Technology Roadmap

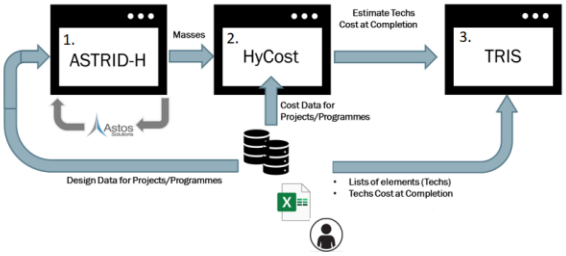


Figure 1: iDREAM integrated framework

The **first capability** of i-DREAM consists in supporting the conceptual and preliminary design of HLSs and related nominal mission. In order to develop this capability, Politecnico di Torino started from upgrading ASTRID-H (Aircraft on-board Systems sizing and Trade-off analysis in Initial Design), a proprietary tool of the research group of Politecnico di Torino developed for almost a decade through research activities, encompassing Master of Science and Doctoral Theses. This tool allows to carry out the aircraft conceptual and preliminary design, the sizing and integration of subsystems for a wide range of aircraft, from conventional to innovative configurations, mainly in the subsonic, supersonic and eventually hypersonic speed regime. ASTRID-H has been validated through the application to various case-studies in several EC funded international projects including the H2020 STRATOFLY (Stratospheric Flying Opportunities for High-Speed Propulsion Concepts) [2] [3] [4]. In this collaboration with ESA, ASTRID-H has been upgraded to support the design of HLSs and to be easily integrated with a dedicated commercial software tool, ASTOS, to automatically perform the mission analysis and to be then integrated into overall iDREAM methodology and framework. In particular, the iASTRID-H for HLS enables two different types of analysis: on one side, the methodology allows to assess and verify an already existing HLS design, on the other side, it guides the users through the definition of a new HLS design and reference mission starting from a set of high-level requirements. This first capability can be exploited in a standalone mode as well as in combination with the other capabilities listed above, as schematically represented in Figure 1.

The HLS design methodology follows a bottom-up approach. Starting from the high-level requirements, the tool estimates the spacecraft characteristics thanks to two main modules: the subsystem mass, power and volume estimation and the mission design routine. These modules work iteratively to obtain the landing system, performance, masses and main dimensions as well as general final budgets of spacecraft masses and fuel needed. For the preliminary design, a first mission study for fuel estimation is elaborated in Python environment and then refined and validated through the ASTOS software, performing the mission analysis, and evaluating the estimated masses.

In case the user wants to verify an already existing HLS design, the activity workflow, reported in Figure 2, has been developed hypothesizing that the following list of inputs is available: main subsystems inputs, as the number of astronaut and the mission duration for the Environment Control Life Support Subsystem (ECLSS), the ΔV suggested values for the preliminary fuel estimation, the Propellants' characteristics, such as the specific impulse, mixture ratio and densities; pressures of the tanks; engines' geometrical characteristics such as number of engines, nozzle exit diameter and expansion ratio; Tanks' material characteristics for the Propulsion, the thermal condition and the heat data for the Thermal Control Subsystem(TCS), the type of communication and input data for Command and Data Handling(CDH), the geometrical data for the structure, the Attitude and Orbit Control Subsystem (AOCS) input data, the Electrical Power Subsystem (EPS) component involved and the payload masses. This set of data can be inserted by the user or can be retrieved from a Database. Specifically, a MySQL Database called TREx has been properly modified to store data of existing HLS projects . If this set of inputs is available, the first fuel mass estimation and the mass breakdown of the different vehicle subsystems budgets can be evaluated following this logic: the first activity consists in the preliminary design of the different subsystems, which are divided in two different categories: (i) Subsystems whose mass, volume and power budgets are related to the propulsive subsystem and to the propellant mass; and (ii) Subsystems which can be considered independent from the propulsive subsystem.

The subsystems, whose size is assumed to be independent from the propellant mass, are ECLSS subsystem, Communication subsystem, Command and Data Handling subsystems, Electrical Power Subsystem, Thermal Control Subsystem.

Complementary, the second category contains those subsystems which are somehow related to the propellant mass and to size them, an iteration cycle with the propulsive subsystem design is necessary as Attitude and Orbit Control subsystem, Structure and Mechanism, Propulsive subsystem

Once the mass, power and volume budgets of the spacecraft are estimated, they can be used as input to initialize ASTOS, to complement the design with a proper mission analysis. Then, when the simulation is completed, the scenario gives in output two reports with the pre-defined plots and the values of the variable of interest (e.g. Final delta V or residual propellant mass) and a comparison between the ΔV provided as initial guess and the ΔV evaluated through the mission analysis takes place. If the difference between the two ΔV is above a certain threshold (to be defined by the user), a new iterative cycle starts again from the vehicle design routine benefitting of the last delta V value calculated with ASTOS. If the difference is below the threshold, the outcomes of the mission analysis routine are used to update the power, mass and volume budget with ΔV of ASTOS because it is more precise than the first assumption used as input data. Please notice that there is another control which involves the propellant mass calculation. If the value calculated by the vehicle design routine is different from the ASTOS value, the tool comes back to the design routine and there is a new study with the new propellant mass value.

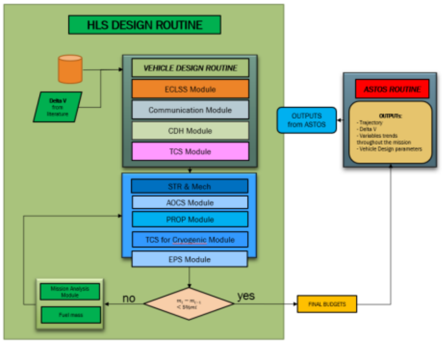


Figure 2: Existing Human Landing System Routine

In case of a New HLS design, the inputs cannot be retrieved from a database and they shall be inserted by the user. These inputs are the same as listed for the previous case. In this case, no connection with the Database is required. In addition, the mass and main dimensions of the spacecraft are estimated, as well as the subsystems final budgets. Then, the mission design routine can be launched. The activity flow is the same as the Existing HLS case. In this case the connection with database is required.

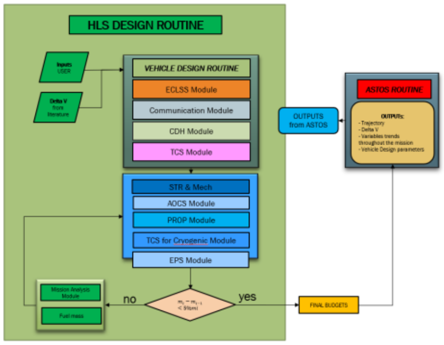


Figure 3: New Human Landing System Routine.

As anticipated in the introduction, ASTOS commercial software has been selected to support the design of HLS with an accurate mission analysis. Benefitting of the outcomes of the vehicle design routines, ASTOS is here adopted to estimates the accurate propellant mass and to simulate its behavior all along a reference mission. At this purpose, one generic input template, to automatically connect ASTRID and ASTOS, have been elaborated to allow a proper integration of the vehicle and mission design routines.

ASTOS routine is not optimized for the HLS phase maneuvers. This is a limitation for the “soft landing phase”.

To get rid of the problem relative to the Soft Landing, the ASTOS Simulation Template has been spitted into two different scenarios: ‘ASTOS’ Descent and ‘ASTOS’ Ascent.

For what concern the first Scenario, it’s composed of 5 different phases. In particular, this scenario it’s used to let the lander reach an almost circular orbit at an altitude of about 15 km. When the lander reaches this situation, it has to land softly on the Lunar Surface. It’s not possible to reach this situation in ASTOS without the optimization.

In order to get rid of this problem, a new routine has been developed in Python environment in order to simulate the soft-landing phase.

The soft-landing routine is a 2-dimensional Dynamic model. This model presents the following strong hypotheses: the initial orbit is an almost circular orbit at @ 15 km, the lander is in the same plane of the target Ground station, no Drag is considered.

Then, the second ASTOS scenario ('ASTOS Descent’) is running. The last phase of the trajectory allows the lander to reach the desired LLO.

The **second capability** of i-DREAM consists in supporting the conceptual and preliminary design of HLSs with the LCC assessment of HLSs. In this case, Politecnico di Torino started from upgrading HyCost, a proprietary tool of the research group of Politecnico di Torino developed especially with ESA, to support a wide range of high-speed vehicles [5] [6] [7]. Using the total dry mass estimated in the design routine or available in users' database, the cost routine can provide insights on the potential development, manufacturing, and operating costs, as well as the cost and price per flight. The cost parameters are suggested by the methodology, including reduction factors for commercial applications or variable learning factor for innovative manufacturing processes. A literature review has been conducted of the main cost estimating methodologies for space systems and programmes. Three main strategies are identified: (i) Analogy, (ii) Parametric, (iii) Engineering build-up . [8] Moreover, several cost models and tools have been considered, such as the Advanced Missions Cost Model (AMCM) and the Unmanned Space Vehicle Cost Model (USCM).

For the application in the scope of this work, the analogy cost estimating methodology is considered best fitting for the following main reasons: the system is considered in its early design stages; not consistent data is available or ever produced on similar systems. However, some available models are used for comparison or validation.

A database is produced considering costs, technical, and performance characteristics of some of the most important crew transportation missions, which may share significant commonalities with the future HLS.

The costs are adjusted for inflation for the fiscal year 2020 and expressed in millions of USD ($FY2020M). Such values are obtained by public sources which may lack in detail. However, information regarding what included in such values (total cost or just part among the development, manufacturing, operating costs) or the price are considered. The technical characteristics include number of units, dry mass, GLOW. The performance characteristics mainly to the payload and the returning payload capabilities.

Some commercial HLS under development are also considered. However, these are analysed mainly in terms of funding received for development, payload mass, difficult.

Once the data was collected, it was possible to compute the distance metric. In this application, such activity was performed using four types of information: (1) crew number, (2) target, (3) GLOW, (4) dry mass. The non-continuous attribute related with the target environment was evaluated with [0, 0.5, 1] values, respectively if same, proximity, or different. The attributes of the future HLS project were assumed as for the requirement document "Requirements for a Human Lunar Lander Test Case" [9] or by average of the database produced.

The **third capability** of i-DREAM consists in supporting the conceptual and preliminary design of HLSs with incremental paths towards the complete maturation of all enabling technologies. In this case, Politecnico di Torino makes benefit of TRIS, an innovative methodology for the generation and update of technology roadmaps to support strategic decisions for a wide range of aerospace product, develop since 2015 in cooperation with ESA [10]- [11] . The methodology is fully integrated into up-to-date conceptual design activity flows. It consists of five main steps that through mathematical and logical models moves from stakeholders' analysis up to planning definition and results evaluation (as reported in Figure 4). Complementary to the traditional experts-based methodologies, the rational process here presented 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, in order to include 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 with respect to key technological, societal and economical aspects [12].

Looking at Figure 4, it is possible to see that TRIS methodology starts from an in-depth analysis of the Stakeholders involved in process. This step is essential to identify from the very beginning of 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 the area of interest which each stakeholder belongs to, it is possible to predict the influence and the interest of each actor. Depending on the influence and interest of each stakeholder, their needs shall be properly weighted, thus allowing to move from a qualitative analysis to a quantitative estimation. In order to complete this transition, it is also necessary to translate the needs expressed by the stakeholders into measurable criteria to be then used during the Prioritization Study.

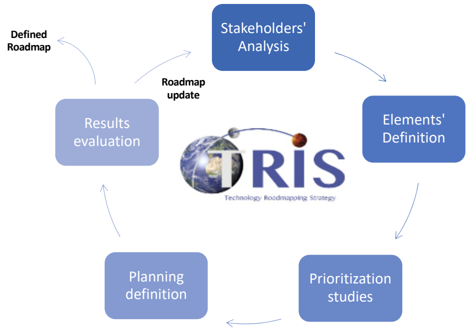
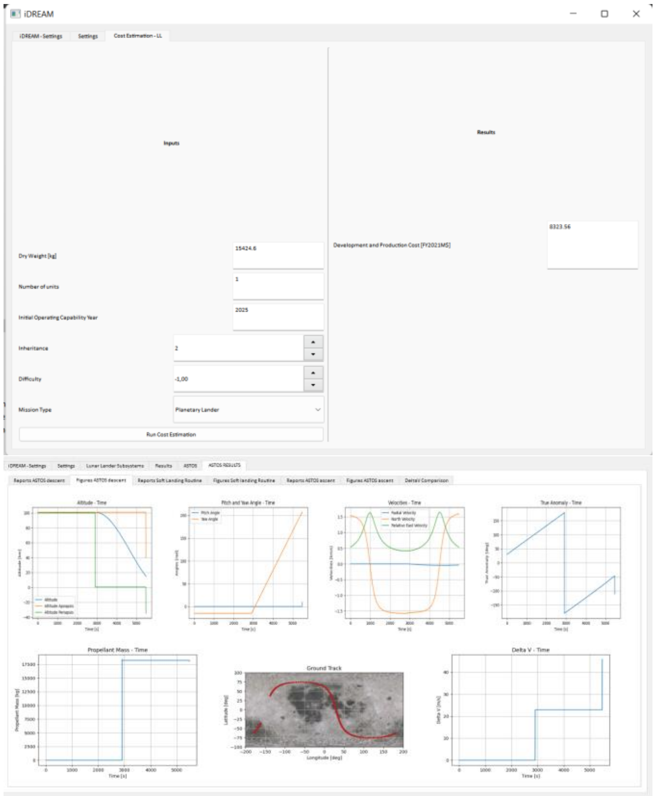


Figure 4: TRIS methodology steps

The second step of this methodology consists in the definition and characterization of lists of elements for each Roadmap pillar, i.e., Mission Concepts and Activities; Operational Capabilities; Building Blocks and Technologies. Again, the availability of a well-structured database helps in defining these lists and into its characterization. In this concept, a specific attention has been given to the definition of the list of technologies and a preliminary estimation of the cost and time resources associated to 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. At this purpose, a new semi-empirical model for time resources allocation is proposed to improve the Planning Definition algorithm, thus increasing the accuracy of time allocation. Eventually, The Results Evaluation step can be considered as 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 onto the final roadmap. This allows also to perform a risk analysis, to associate 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 on the basis of the expected revenues, which can be expressed as stakeholders' criteria, thus analysing the impact of stakeholders' expectations onto the final roadmap.

iASTRID-H, HyCost and TRIS can be used in standalone mode as well as into the integrated framework reported in Figure 1. Each of these capabilities has been implemented in a Phython environment with a dedicated Graphical User Interface (GUI) to help the users in speeding-up the prototyping of a new HLS or verification of an existing one (Figure 5).



Dry Weight [kg] 15424.6

Number of units 1

Initial Operating Capability Year 2025

Inheritance 2

Difficulty -1,00

Mission Type Planetary Lander

Development and Production Cost [FY2021M$] 8323.56

Figure 5: Screenshots from iDREAM GUI

3. APPLICATION TO THE ESAS LSAM

The case study presented here is based on ESAS LSAM spacecraft [13] [14]. The Lunar Surface Access Module, fully designed and manufactured by ESAS team supported by NASA, is one of the most complete HLS project of these years. It combines the latest manufacturing technologies with the capability of multiple lunar missions.

ESAS LSAM is composed by 2-stage . For the validation is considered as 1-stage which includes the ascent and descent modules (Figure 6). The analysis is focusing on the descent mission phases where the ascent module with the corresponding fuel mass are considered as payload masses.

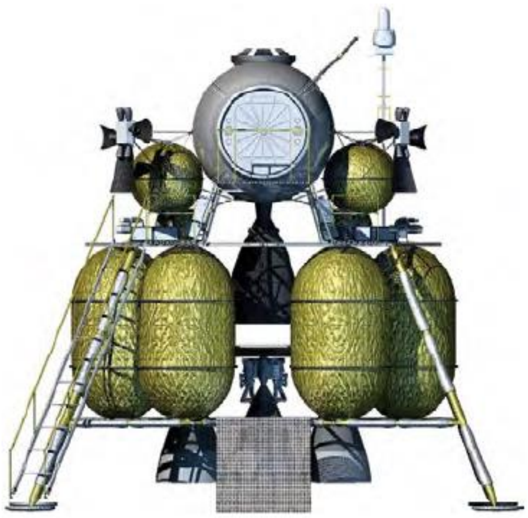


Figure 6: ESAS LSAM CONFIGURATION [14]

3.1 ESAS LSAM DESIGN AND MISSION ANALYSIS

The results reported in this section are coming from the Preliminary Design and Mission Analysis performed for an Existing Case.

In particular, a quite important set of Functional and general Requirements to initiate the analysis with details on the Vehicle Configuration are collected from Table 1 to Table 3.The subsystems considered are: Environment Control Life Support subsystem (ECLSS), the Propulsion subsystem, the Electrical Power Subsystem (EPS) , Structure, Avionics and ‘Other component’ study. The ‘Avionics’ includes the Communication, Command and Data Handling(CDH) subsystem and Attitude and Orbit Control Subsystem (AOCS) . ‘Other component’ includes the Thermal Control Subsystem (TCS). [15]

Table 4 reports the main results achieved exploiting the iASTRID-H methodology and tool compared with the actual values of the ESAS LSAM. General errors lower than 10% obtained, thus perfectly in line with a conceptual design phase. Errors greater than 10% are caused by a smaller amount of specific LSAM subsystem data collected in the literatures. [13] [14] [15]

Table 1: General Requirements.

	Functional requirements
R.1	The HLS shall be commanded and controlled using humans in the loop.
R.2	The HLS crew shall allow to monitor, command, control, and recover the propulsion subsystem ot the HLS flight vehicle
R.3	The HLS shall be able to communicate with the LOP-G at any given time.
R.4	The HLS shall be able to used and re-used multiple times (up to 5 times)
R.5	The HLS shall be able to ascend and manoeuvre back to docking with the LOP-G.
R.6	**Interface requirements**
R.7	The HLS shall be able to arrive to and depart from the LOP-G and land of the Moon using humans in the loop.
R.8	**Environmental requirements**
R.9	The HLS shall be able to sustain the environment (day/night) of the Moon South pole and the arrival to and departure from the LOP-G.
	Operational requirements
R.10	The HLS shall be able to accommodate **4 astronauts**.
R.11	The HLS shall allow stay on the surface of the Moon for up to 72 hours during the Lunar Day.
	Implementation requirements
R.12	The HLS module shall include the following subsystems: Propulsion, avionics (GNC, OBC etc.), ECLSS, TCS, Comms, Structure, Power for all elements of HLS (ascender and descender).
R.13	The HLS module shall deliver the following outputs: **R13.1.** Mission and Vehicle Performance (propellant mass, ΔV, trajectories etc) **R13.2.** System budgets; mass, power, volume

Table 2: Performance and Configurational Requirements – Vehicle Configuration. [14] [15]

Global Input Variable Name	Value
Number of stages	1
Nominal payload mass [kg]	4161
DELTA V DATA	
Lunar Orbit Insertion phase [m/s]	1100
Descent phase [m/s]	1900
Number of Oxidizer tank	6
Number of Hydrogen tank	2
COMMUNICATION SUBSYSTEM	
Communication type	S-band
EPS SUBSYSTEM	
Batteries type	Li-ion

Number of batteries	4
Fuel cells type	PEM
Number of Fuel cell	3
ECLSS SUBSYSTEM	
Number of astronauts	4
Mission time [day]	7
Pressurized volume [m2]	31.8
Radius habitat volume [m]	3
Length habitat volume [m]	5

Table 3: Performance and Configurational Requirements – Propellant Characteristics.

Global Input Variable Name	**Value**
Stage 1 Propellant	LOX/LH2
Stage 2 Propellant	LOX/CH4
Mixture Ratio propellant stage 1	6
Vacuum Isp propellant stage 1 [s]	451
Oxidizer density stage 1 [kg/m^3]	1142.0
Fuel density stage 1 [kg/m^3]	810.0
Mixture Ratio propellant stage 2	3.5
Vacuum Isp propellant stage 2	310
Oxidizer density stage 2 [kg/m^3]	1142.0
Fuel density stage 2 [kg/m^3]	800
Stage 1 Propellant	Liquid
Stage 2 Propellant	Liquid

Table 4: Results of iDREAM iASTRID-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	-3,5
Avionics mass[kg]	678	655	4
Propulsion mass [kg]	3810	3905	-2
Structure mass [kg]	2965	2841	4
EPS mass [kg]	1310	1246	5
Other mass [kg]	1155	1022	13
Dry mass [kg]	10421.3	11264	-5
Wet mass [kg]	40163	45861.6	-12
Fuel mass [kg]	25580.7	29820	-14

The study estimates the fuel mass with an error of 14% for both references document: the scenario of the ESAS mission foresees the insertion into lunar orbit with the crew exploration vehicle (CEV) connected [13]. Meanwhile, the iDREAM validation considers only the ascent module connected to the descent module during the whole analysis of the scenario.

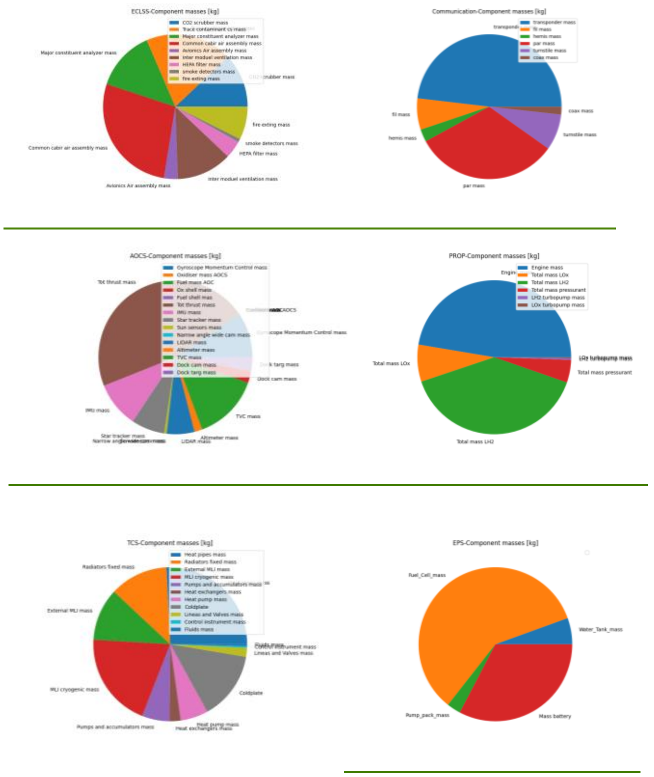


Figure 7: ESAS LSAM Mass Breakdowns estimated by iASTRID-H

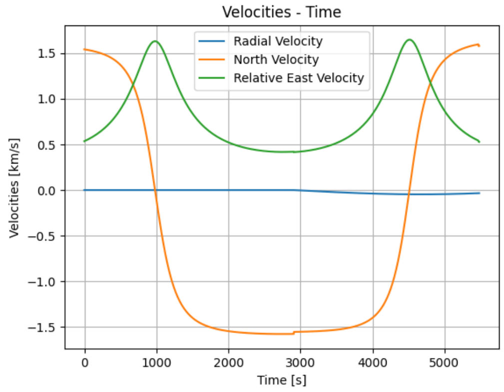


Figure 8: Velocities in function of time estimated by iASTRID-H

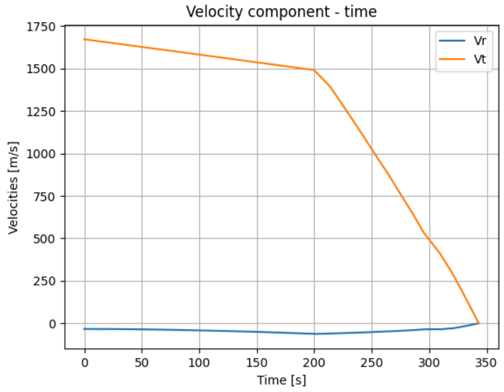


Figure 9: ESAS LSAM Velocities profile as obtained with Soft-landing routine.

3.2 ESAS LSAM COST ESTIMATION

The results achieved by iASTRID-H are used as inputs to run Cost Estimation Routine (HyCost). Moreover, to complete the LCC assessment with sufficient details to be then used by the Technology Roadmap Routine, typical cost parameters are provided in the cost routine. These are editable by the user and includes programmatic data such as the number of stage, the dry mass, the difficult of production prose and the mission year(Table 6). At this purpose, some hypotheses have been added. 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). The results are very close to the reference cost values, providing a good case study for tool validation. The subsystems costs are grouped in technology categories to assess the technology cost at completion (CaC) used for the roadmap routine.

Table 5: Results Comparison.

ID	**Development and Production Cost[M]**
ESAS LSAM [13]	5500
ESAS LSAM [iDREAM]	5993
Percentage differences ([%])	9

Table 6: HyCost - Techs CaC Estimation.

Global input variable name	**Value**	**Unit**	**Variable Description**
Dry_mass	15424,6	kg	ESAS LSAM Dry mass
Num_units	1	/	Number of units
Initial operating capability year	2025	/	Initial operating capability year
Inheritance	2	/	Inheritance degree
Difficult	-1	/	Difficult of design process

3.3 HLS TECNOLOGY ROADMAP

In order to generate the technology roadmap, the following set of inputs has been set [15]:

- Start Date: 01-01-2005 (ESAS LSAM vehicle)
- End Date: 31-12-2025 (first LSAM Mission)
- Target TRL: 9
- Out of Nominal Scenario
  - Extra-cost [%]: 0
  - Extra-time [year]: 0
  - Time delay cost [M€/year]: 32

Examples of results obtained are reported in the following Figures.

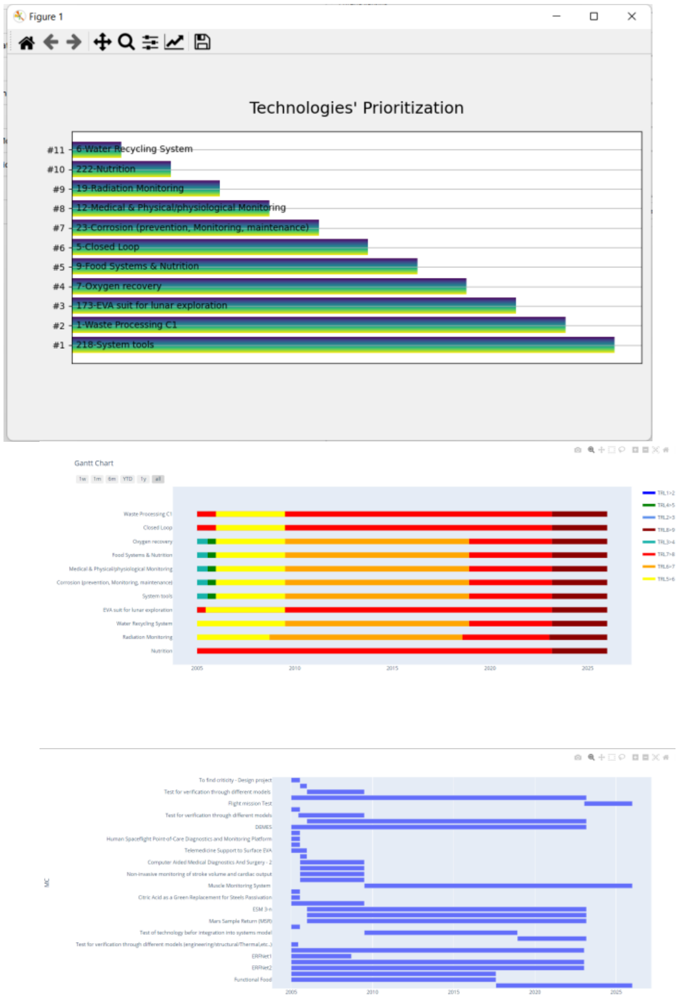


Figure 10: HyCost Cost Breakdown for ESAS LSAM

4. CONCLUSIONS AND FUTURE WORKS

This paper has described the methodology developed at Politecnico di Torino to support the European Space Agency in the Human Landing System design activity and to complement the traditional conceptual design with a multidisciplinary set of analyses which includes a thorough assessment of the economic and technological viability of the solution. The results of the validation of the overall design methodology has revealed errors lower than 10% in average, perfectly in line with the expectations of a conceptual design phase.

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