Rapid prototyping for Martian space systems

Rapid prototyping for Martian space systems

Giuseppe Governale, Jasmine Rimani, Giuseppe Narducci, Nicole Viola, Roberta Fusaro

Politecnico di Torino
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Moving To Mars (M2M) 2022 Workshop
Montreal, Canada

Overview

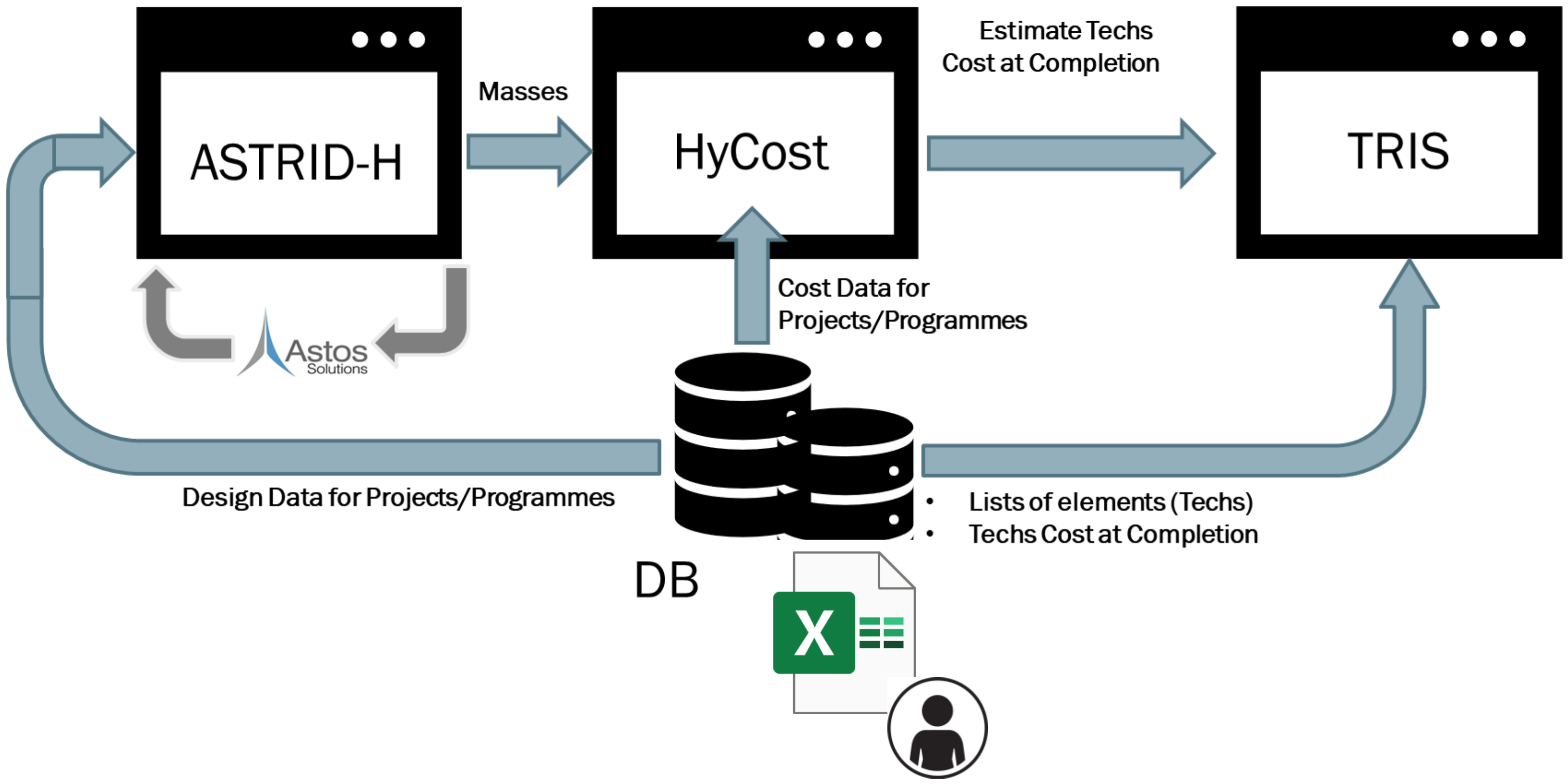
1. **iDREAM** overview and its capabilities

   for **microlaunchers** and **lunar vehicle**

   - **Database HyDAT**
   - **Design iASTRID-H**
   - **Cost HyCost**
   - **Technology Roadmap TRIS**

2. **iDREAM Mars application**

iDREAM Integrated Framework



1. **iASTRID-H**
   Design and Mission Analysis
   - Mission Analysis in ASTOS

2. **HyCost**
   Cost estimation - LCC assessment

3. **TRIS**
   Technology Roadmap

Database - HyDat

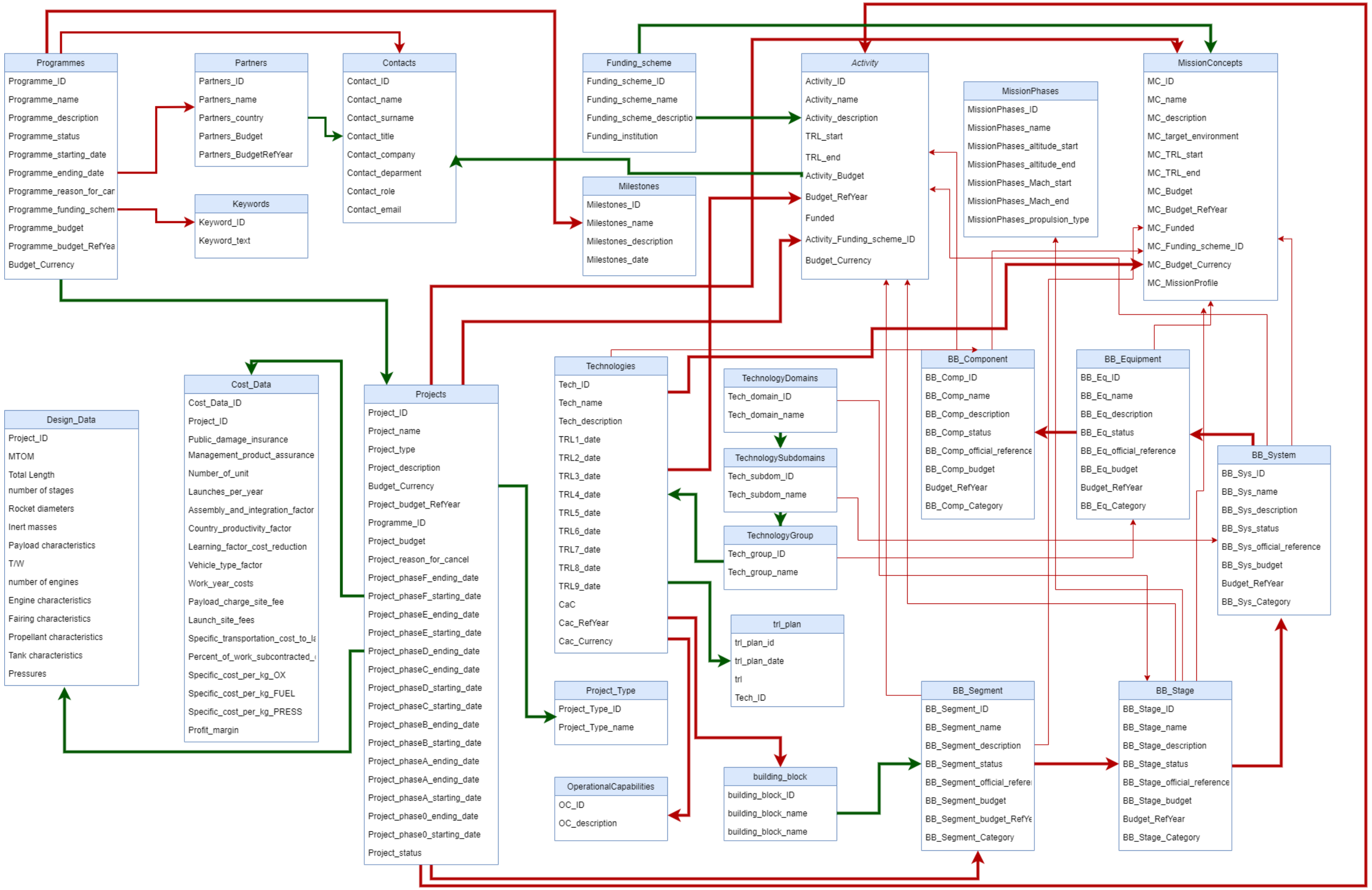
Heritage of POLITO technology roadmapping database for

- ✓ Hypersonic transportation systems
- ✓ Reusable access to space vehicles

A **MySQL database** supporting the whole iDREAM framework:

- o Design & mission analysis
- o Cost Estimation
- o Technology Roadmap

Equipped with unified connection by an ad-hoc developed **Database Management Library** for the operations of data input/output from/to the database throughout the tool modules.



iDREAM Microlaunchers

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Design Routine – ASTRID H ML

Design Philosophy

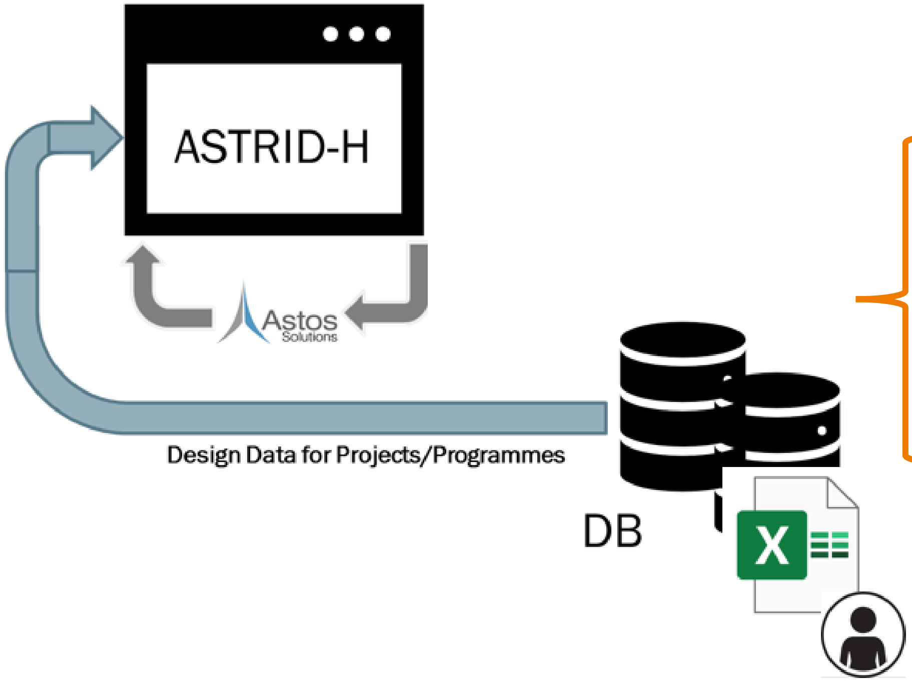
The microlaunchers design methodology follows a **top-down approach.**

From high-level requirements to subsystems design through the vehicle main parameters.

Design Routine Logic

Inputs from **DATABASE** (or **User**)

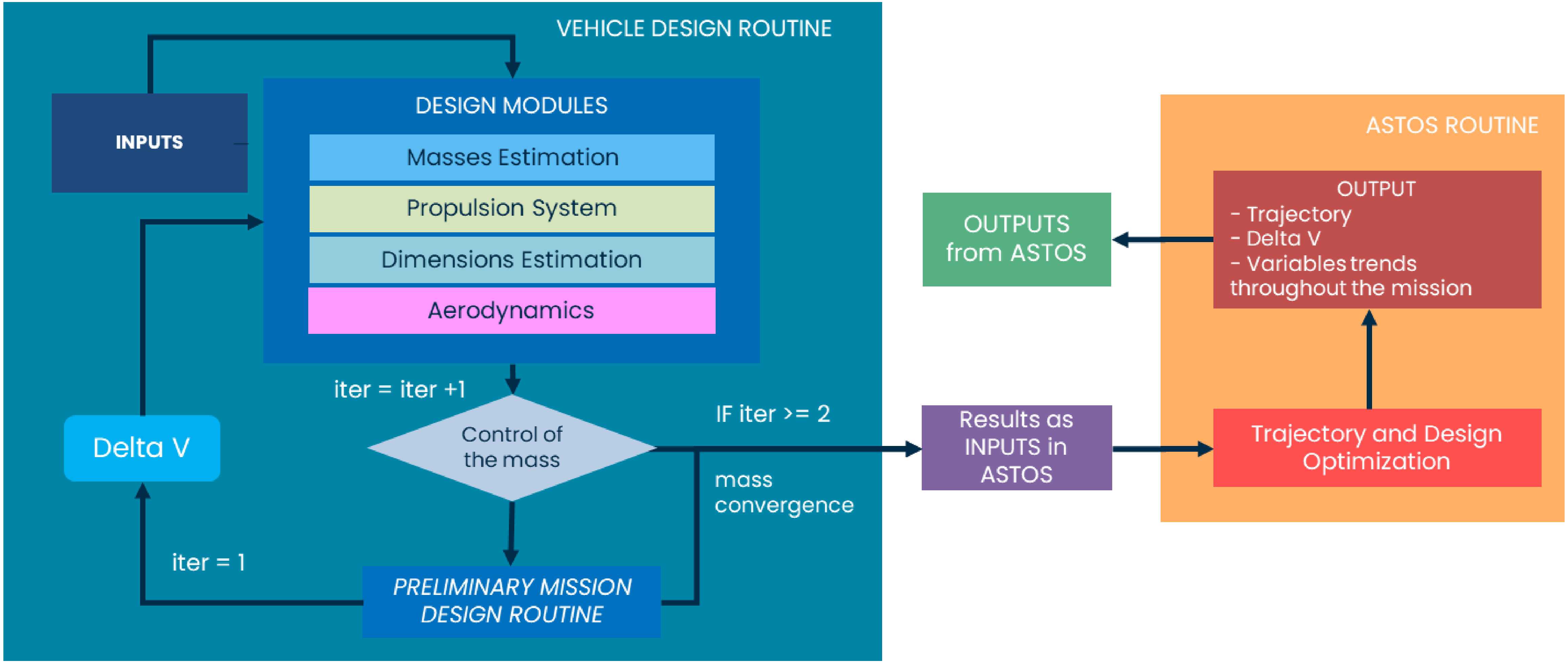
- ✓ **Mission data** (target orbit, launch site, inclination and launch azimuth)
- ✓ Nominal **Payload Mass**
- ✓ **Propellants' characteristics** (specific impulse, mixture ratio and densities)



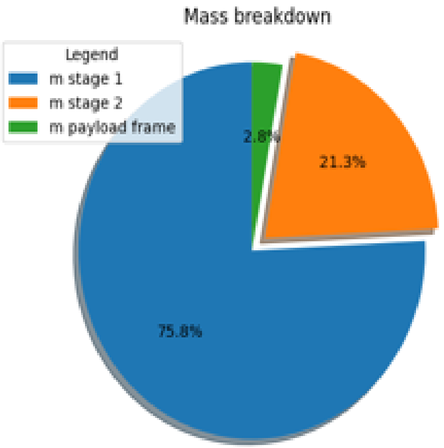
Outputs

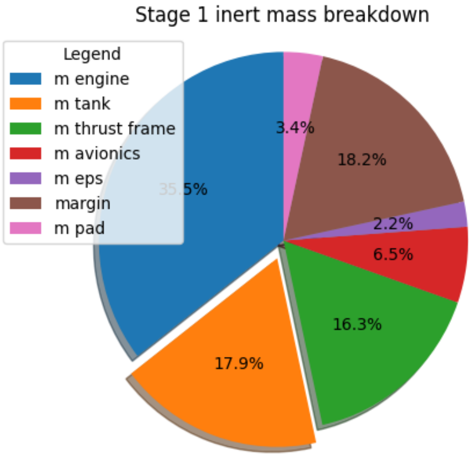
- ✓ **Vehicle geometry and Layout**
- ✓ **Vehicle performance**
- ✓ **Mission Concepts**

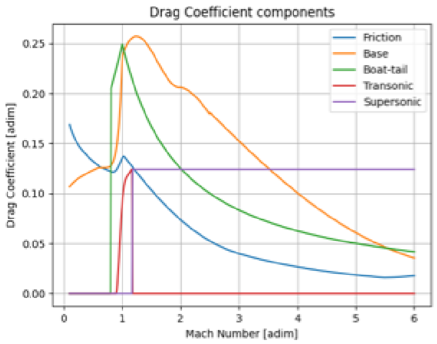
Microlauncher Design Routine

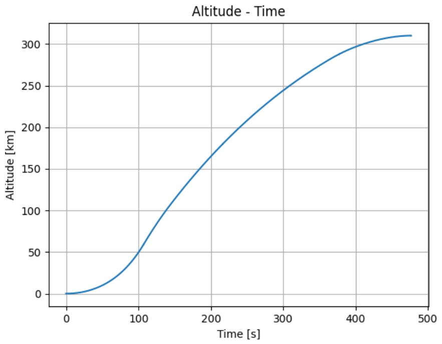


MicroLauncher Design Routine– Outputs









Global Input Variable Name	iDREAM – Preliminary Design	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

[*] Electron – User's Guide

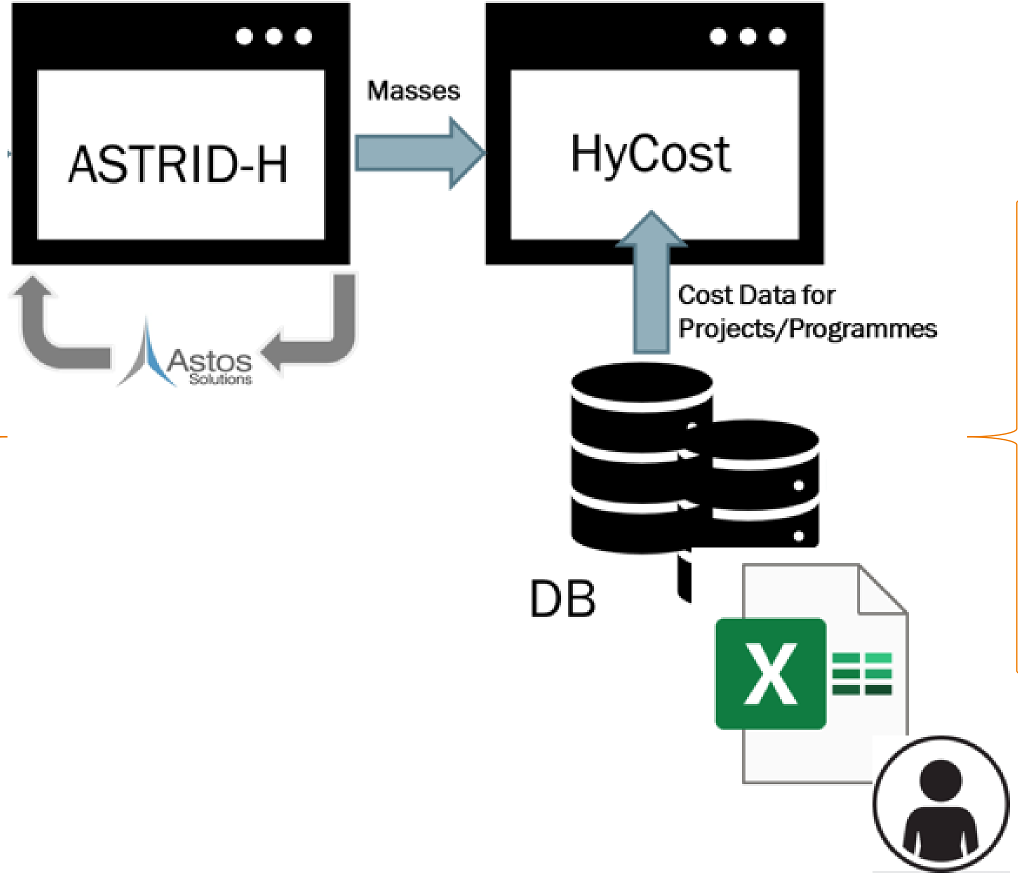
Cost Estimation routine – HyCost ML

Inputs from **DATABASE** (or User)

- ✓ **Cost parameters**

Inputs from **DESIGN routine** (or User)

- ✓ **Pressurizant Tank** mass
- ✓ **Fuel Tank** mass
- ✓ **Oxidizer Tank** mass
- ✓ **Stage structure** mass
- ✓ **Engine(s)** mass
- ✓ **Thrust Vector Control** mass
- ✓ **Pipes** mass
- ✓ **Valves** mass
- ✓ **Stage Harness** mass
- ✓ **Payload** mass
- ✓ **Avionics** mass
- ✓ **Attitude** mass
- ✓ **Interstage** mass



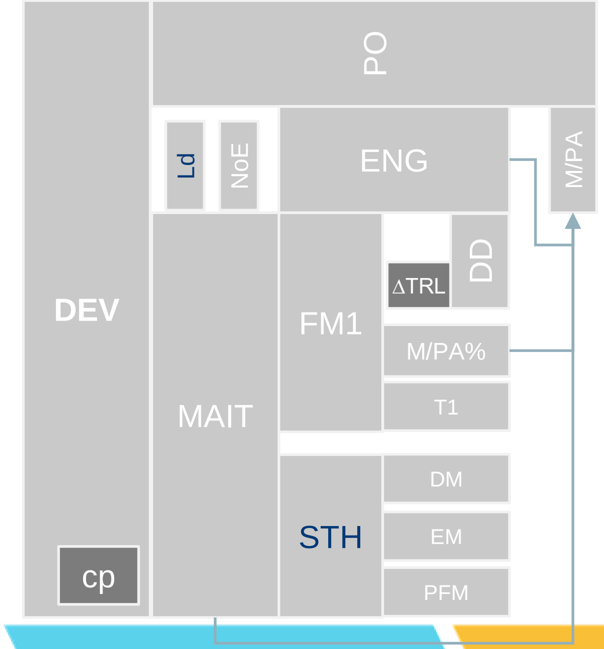
Outputs

- ✓ LCC assesment
  - **Development** cost
  - **Operating** cost
  - **Manufacturing** cost
  - **Cost per flight**
  - **Price per flight**
- ✓ Technologies Cost at Completion

Cost Estimation Methodology ML

Based on T1 equivalent units

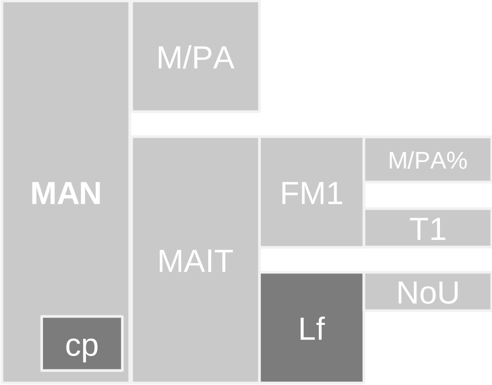
Applicable at subsystem and equipment level



$T1 = a * Mass^b$

a, b, regression coeff.

[historical subsystem data]



based on Drenthe, 2016

Commercial factor ML

Scaling factor (cp) considering commercial applications:

less subcontractors, more profit retain.

Considered in both development and manufacturing costs.

Table 3.2: Proposed scaling of Management, Product Assurance and I&T [45]

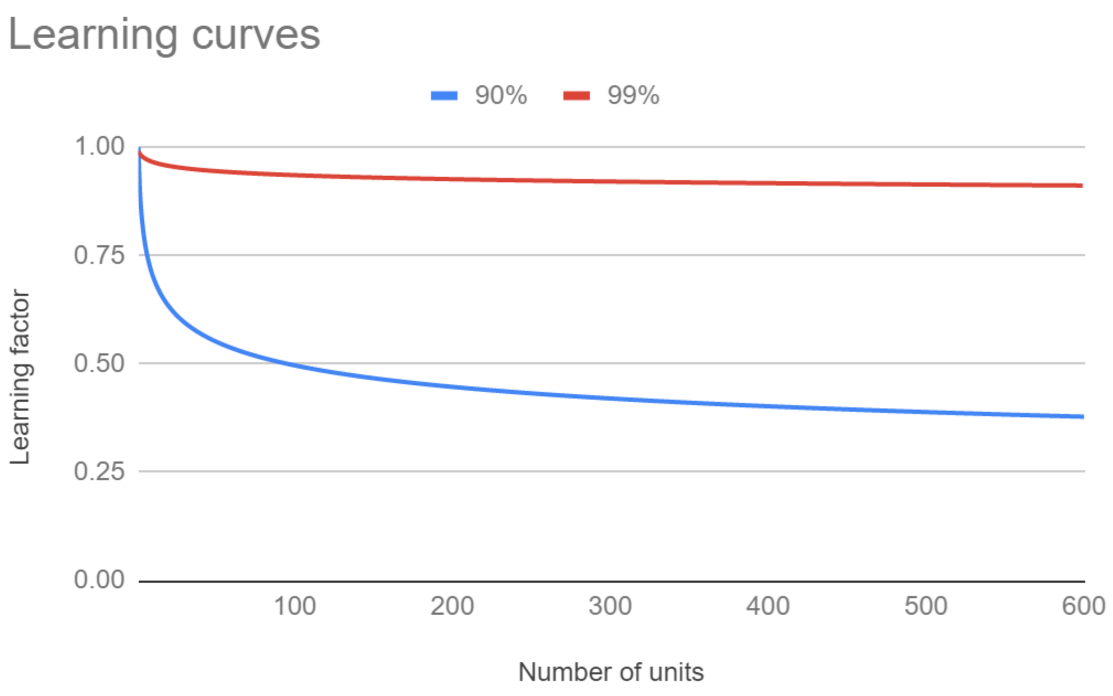
	Scale Factor S_m	2.85
	Original Cost Contributions	**Scaled Commercial Cost Contributions**
Management (M)	10%	3.5%
Product Assurance (PA)	5%	1.8%
Integration & Test (I&T)	9%	3.2%
Total Development Cost Contribution	26%	8.6%
Cost Reduction		**-13.7%**

Learning factor ML

Mainly in the manufacturing costs, different learning curves wrt to the process

- 3D printing (99%)
- Traditional manufacturing (90%)

Azul Costs	[k€]	[k€]
MAN (t) 3D print.	501,823	23,186
MAN (t) BaU	478,637	
MAN (u) 3D print.	10,036	464
MAN (u) BaU	9,573	
3D printing	**delta**	**+4.8%**



PROs	CONs
lower unit cost for new components	not decreasing with production volume
less parts, easier integration	lower Stress/Number of Cycles curve
faster and less workers	high raw material cost

3D printing features

Technology Roadmap routine - TRIS

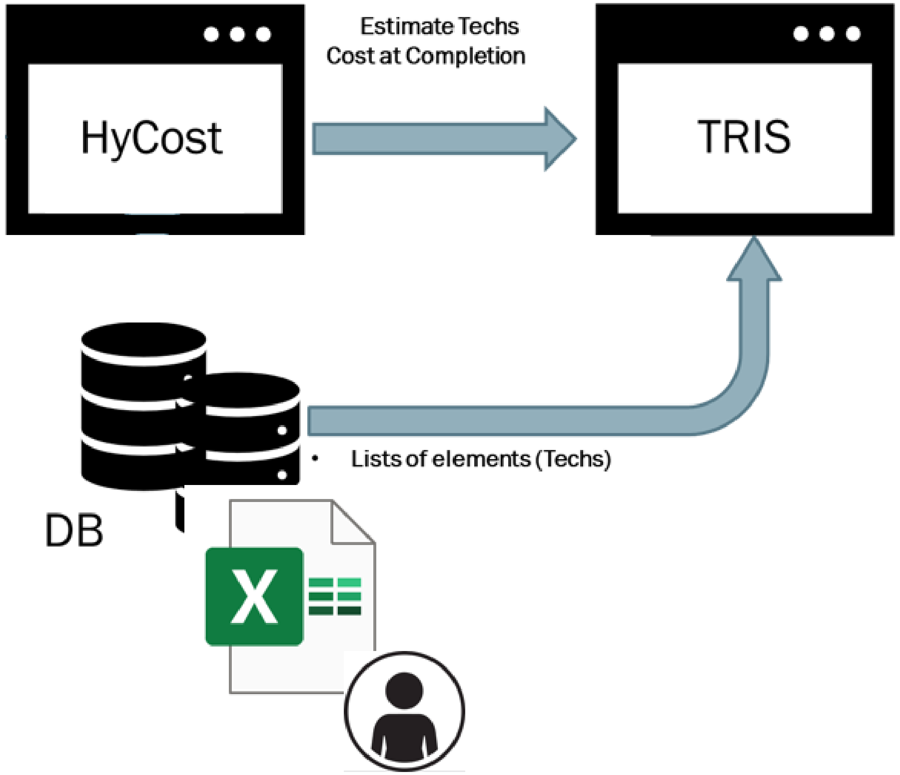
Technology Roadmap Philosophy

To generate technology roadmaps in support of strategic decisions, highlighting possible incremental paths towards the end-goal thanks to the exploitation of common System Engineering tools and processes.

Technology Roadmapping Routine Logic

Inputs from **DATABASE** (or User) and **COST ROUTINE**

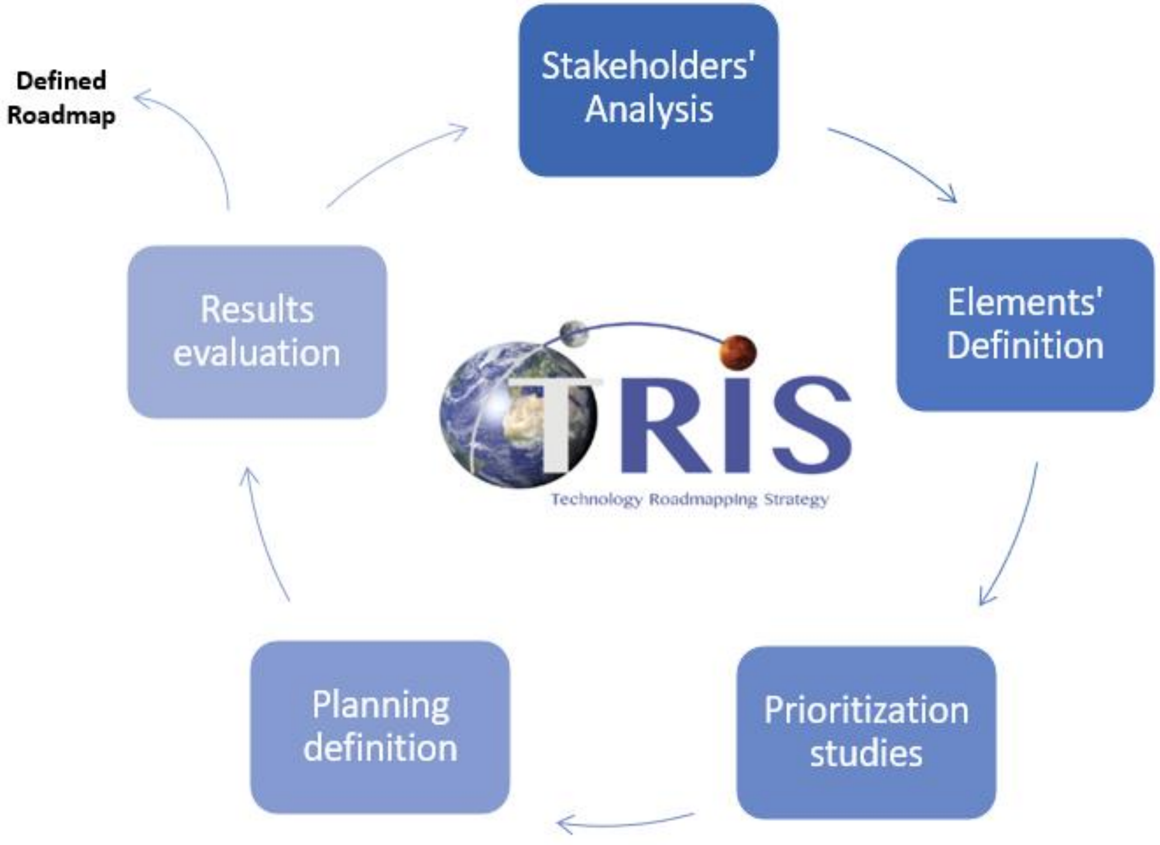
- ✓ **Stakeholder lists and characterization**
- ✓ **Elements lists:**
  - Building blocks
  - Mission Concepts
  - Operational Capabilities
  - Technologies
- ✓ **Elements characterization**
  - Links between elements
  - TRL
  - Costs
  - …



Outputs

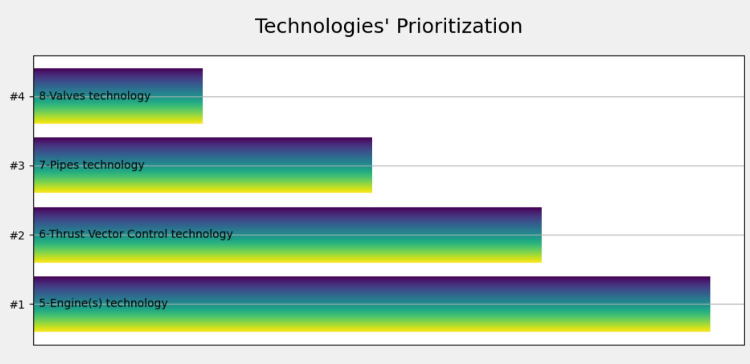
- ✓ **Technology roadmap**
  - Techs prioritization
  - Mission concepts prioritization
  - Techs planning
  - Mission concepts planning

Technology Roadmap methodology



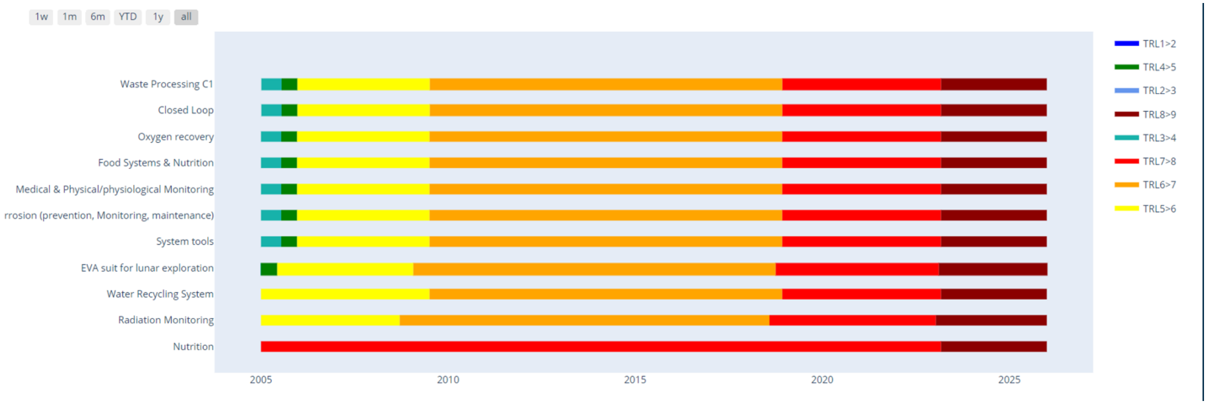
Steps of the developed technology prioritisation methodology.

Prioritization Studies



The list of technology and activities are ordered as for the Stakeholders needs.

Planning definition



iDREAM Human Landing System

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Design Routine – ASTRID H HLS

Design Philosophy

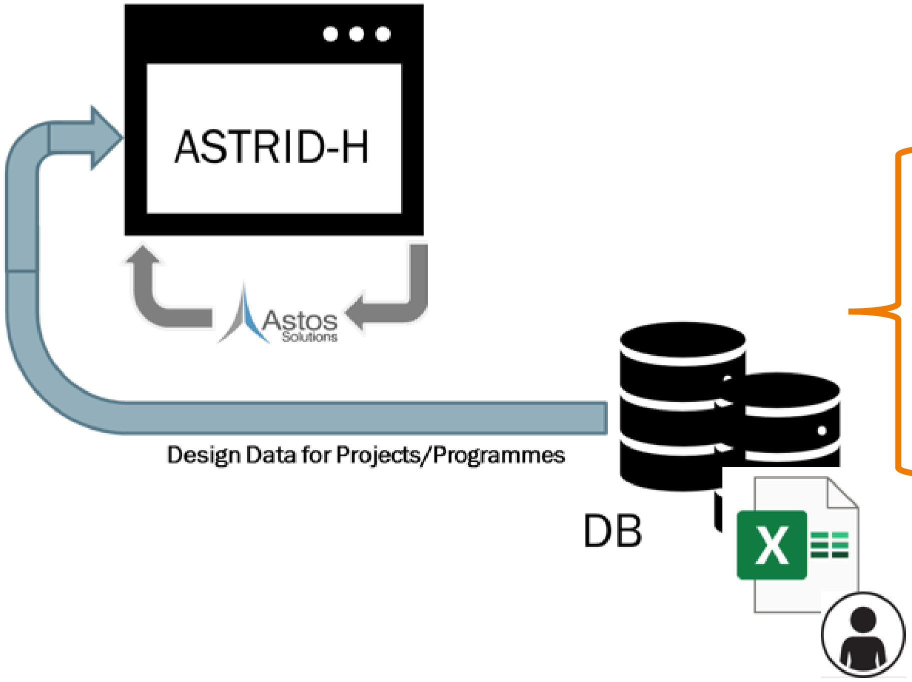
The human landing system **design** methodology follows a **bottom-up approach**.

From subsystems to the whole vehicle design.

Design Routine Logic

Inputs from **DATABASE** (or **User**)

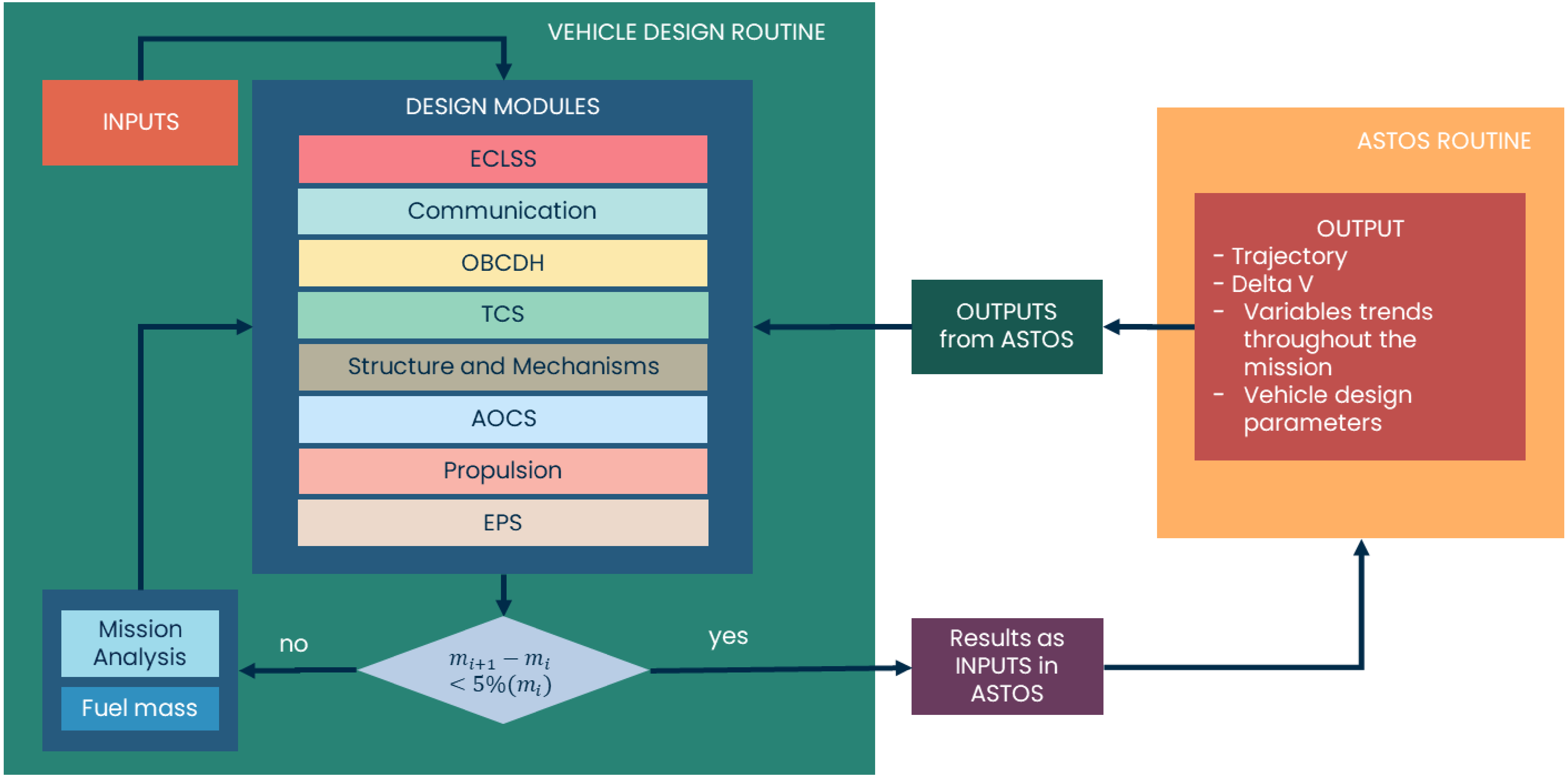
- ✓ **Mission** data**:** estimated deltaVs, mission phases time
- ✓ Nominal **payload mass**
- ✓ **Number of crew**
- ✓ Total **mission time**
- ✓ **Subsystems** data: PROPULSION, ECLSS, COMM, CDH, AOCS, TCS, STR, EPS)



Outputs

- ✓ **Vehicle geometry and Layout**
- ✓ **Vehicle performance**
- ✓ **Mission Concepts**

Human Landing System Design Routine



Cost Estimation routine – HyCost HLS

Cost Philosophy

The human landing system **cost** methodology is based on the Advanced Mission Cost Model (**AMCM**)

Additionally, a cost estimation based on the analogy method was developed.

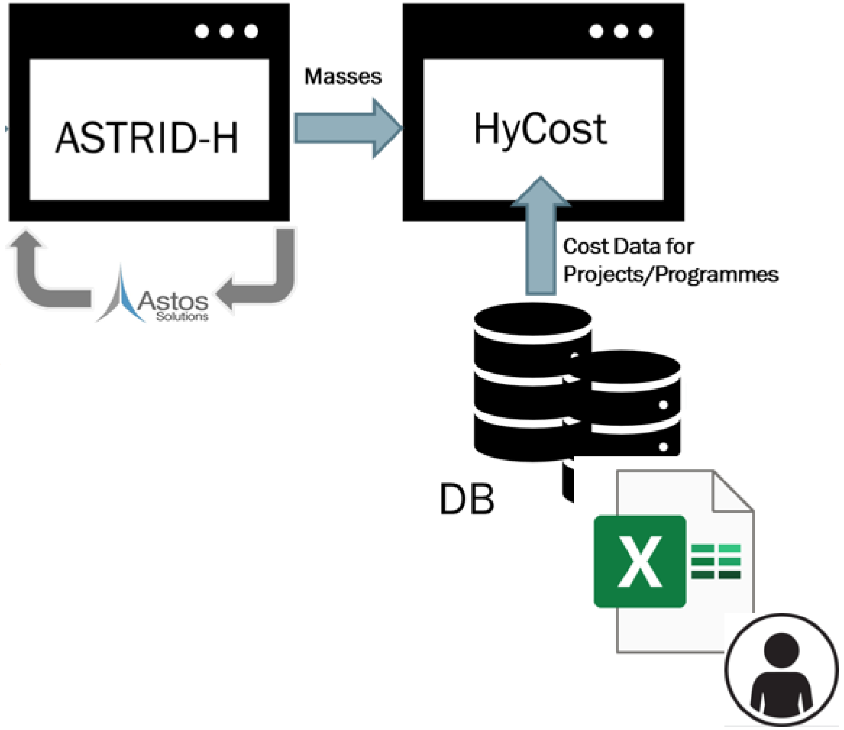
Cost Routine Logic

Inputs from **DATABASE** (or User)

- ✓ **Number of units**
- ✓ **Initial Operating Capability year**
- ✓ **Inheritance**
- ✓ **Difficulty**
- ✓ **Mission Type**

Inputs from **DESIGN routine** (or User)

- ✓ **Dry mass**



Outputs

- ✓ LCC assesment
  - **Development** cost
  - **Operating** cost
  - **Manufacturing** cost

Human Landing System - Cost Estimation - Validation

The budget allocated for the HLS in the Artemis program is

21,300 $FY2020M

The result of the cost estimation by analogy for the HLS is

18,619 $FY2020M

The result of the AMCM cost estimation is equal to

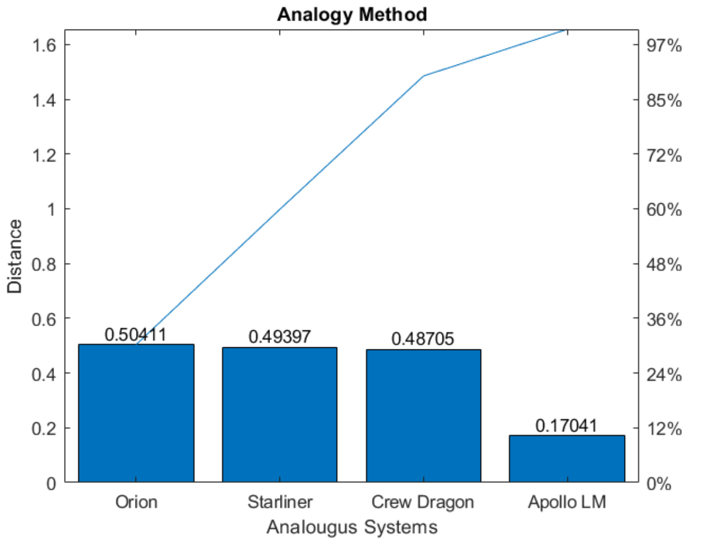
17,618 $FY2020M

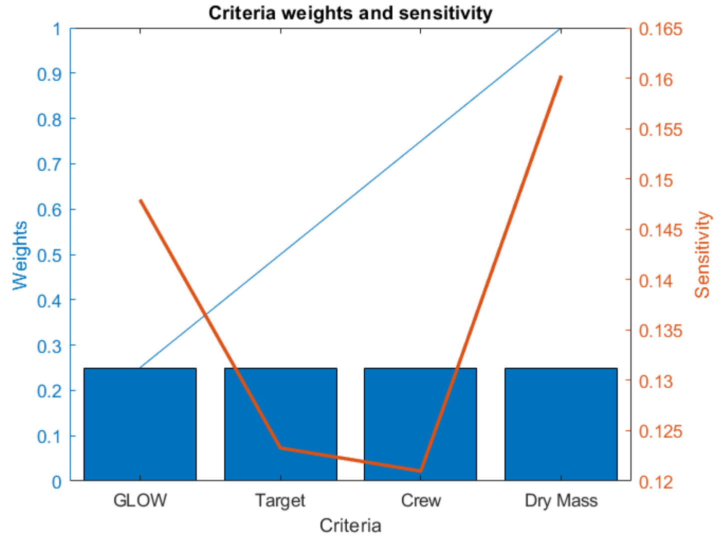
-14%

from the allocated budget

+5%

from the AMCM model





iDREAM Mars

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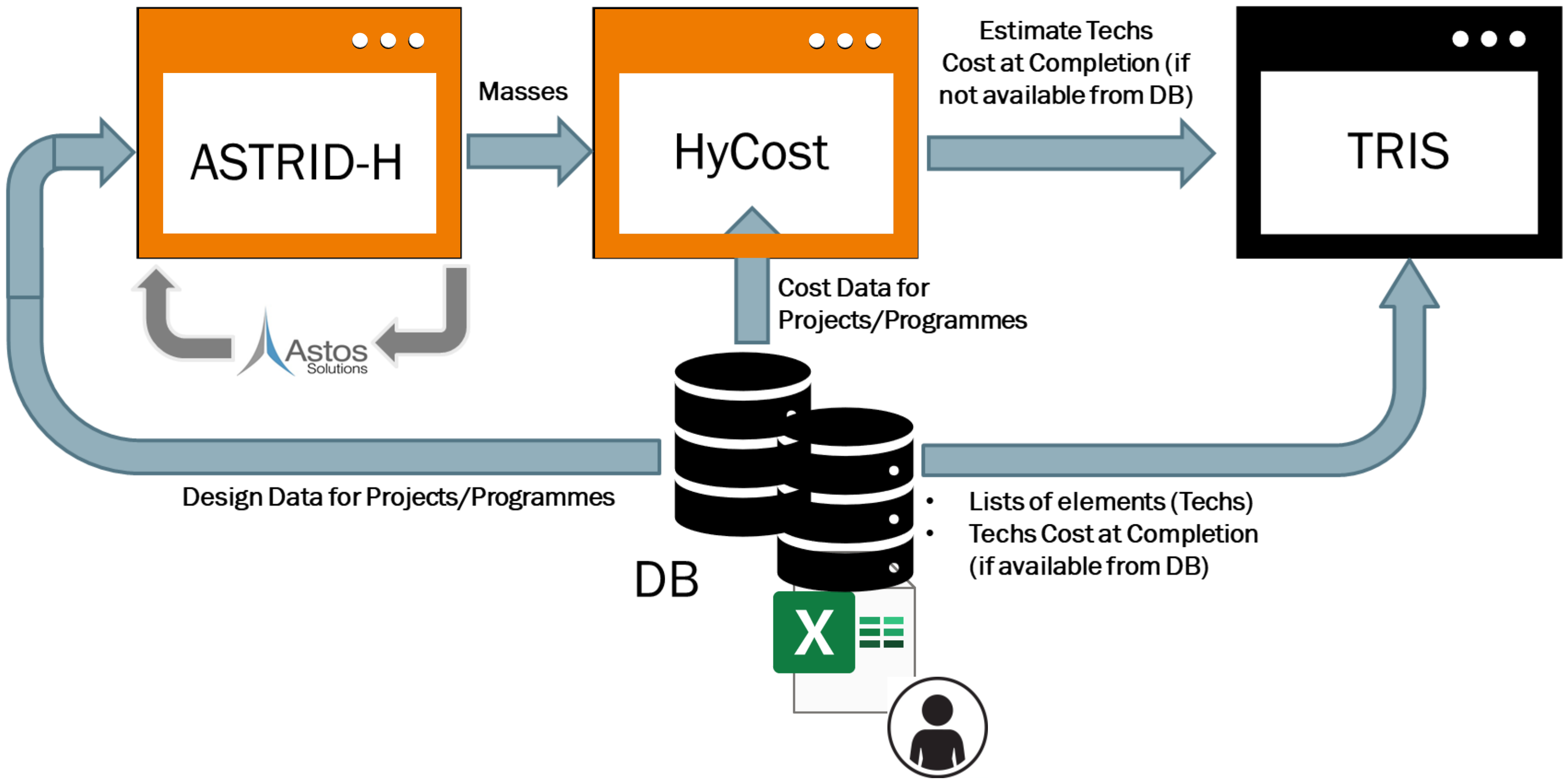
iDREAM for Mars



DESIGN

1. Propulsion
   i. Nuclear or others
2. ECLSS
   i. Lower in %mass
   ii. Artificial gravity

COST

1. AMCM
2. Analogy method

Conclusions

iDREAM is an integrated vehicle design routine with the capabilities of:

- ✓ providing a preliminary design of the studied system
- ✓ estimating the overall life-cycle cost of the designed system
- ✓ supporting the evaluation of technology roadmaps

The three modules of iDREAM can be used as standalone software

- ✓ iDREAM has been validated for microlaunchers and lunar applications.

iDREAM will be extended to provide design, life-cost assessment and technology roadmapping analysis for other space systems, such as Mars missions, for both orbital and surface systems

- ✓ The HyDat database is continuously updated
- ✓ An overview of the main affecting changes to the iDREAM routines has been presented for the Mars case

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Thanks for your attention

Any questions?

Validation Study

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MicroLauncher Design Routine– Inputs

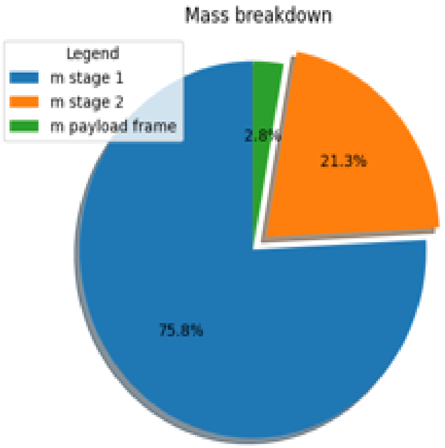
The **Electron** launch vehicle is fully designed and manufactured by **Rocket Lab**. It combines the latest manufacturing technologies with the capability of multiple launch ranges in a domestic launch site (Mahia Launch Complex or Rocket Lab Launch Complex).

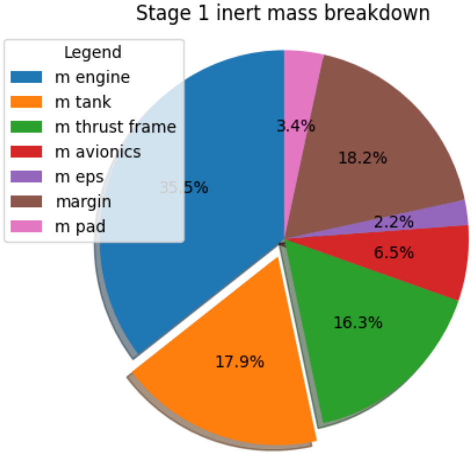
Electron exists both as a 2-stage and as a 3-stage configuration. In this case, the 2-stage architecture is analysed

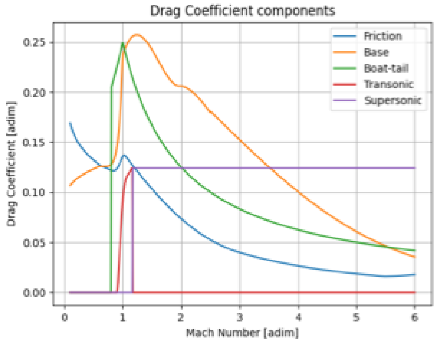
Vehicle design inputs

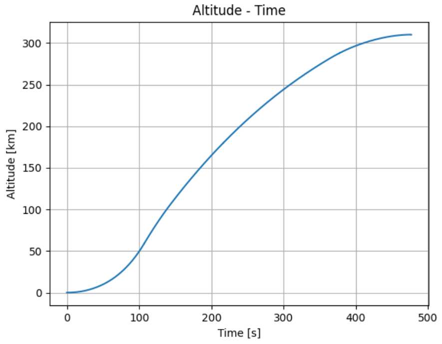
Global Input Variable Name	Value
Target Orbit [km]	300.00
Orbital Inclination [deg]	45
Launch site selection	Mahia, New Zealand
Number of stages	2
Nominal payload mass [kg]	200.0
Rocket diameters [m]	1.2
Thrust over weigth stage 1	2.0
Thrust over weigth stage 2	0.95
Maximum Take Off Mass [t]	12.5
Total Length [m]	18.0
Stage 1 Propellant	LOX/RP1
Stage 2 Propellant	LOX/RP1
Number of engine first stage	9.0
Number of engine second stage	1.0

MicroLauncher Design Routine– Outputs









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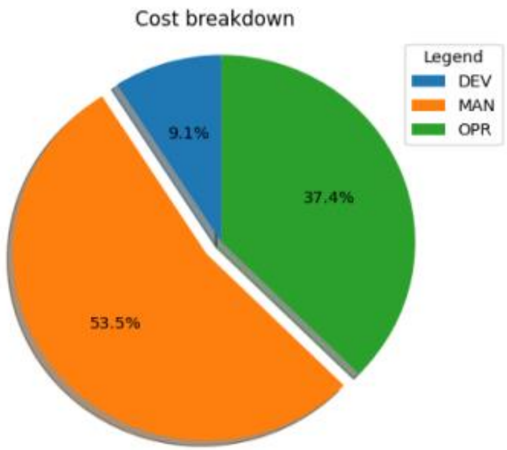
[*] Electron – User's Guide

MicroLauncher Cost Estimation Routine – Outputs



	Price per Flight [M€]	Specific price [k€/kg]
Electron	16	54
iDREAM	17	52
Percentage differences [%]	7%	-4%

ML Backup

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Microlaunchers design methodology

Main Requirements

- ✓ i-DREAM shall support the **conceptual and preliminary design** of Microlaunchers (MLs) and related **reference missions**.
- ✓ For the Mission Analysis, iDREAM shall make benefit of the commercial software ASTOS.

- ✓ The ML design methodology shall enable two different types of analysis:
  - Assessment and verification of an already existing ML design (**Existing routine**) supported by the HyDat Database
  - Definition of a new ML design and reference mission starting from a set of high-level requirements (**New routine**)

Expected Tool Developments

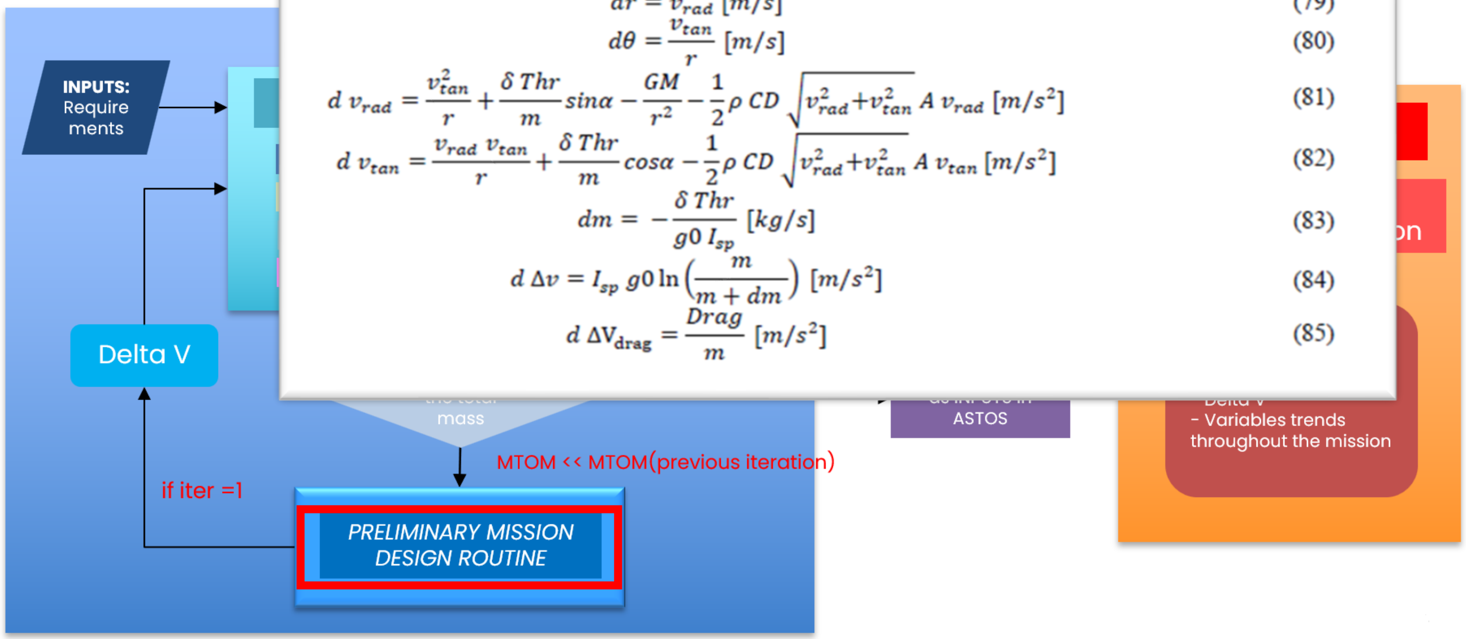
- ✓ Upgraded version of **ASTRID-H** (Aircraft on-board Systems sizing and TRade-off analysis in Initial Design)
  - ASTRID-H is a proprietary tool of the research group of Politecnico di Torino, developed for almost a decade through different research activities.
  - ASTRID-H has been validated for the conceptual and preliminary design of a wide-range of transportation system from civil aviation to access to Space and beyond.
- ✓ Exploitation of **ASTOS** commercial software to support the design of MLs with reliable and accurate Mission Analysis.
- ✓ Upgraded version of **HyDat** , a database developed by Politecnico di Torino to support technology roadmapping activities of ESA for hypersonic transportation systems and Reuseble Access to Space Vehicles

Micro-Launcher Design Routine (III)

Preliminary Mission Module ->

1) First trajectory estimation;
2) Variable trends throughout the mission;
3) **Delta V** and **Gravity** and **Drag Losses.**

Starting point for new iterations!



$$dr = v_{rad}\ [m/s] \tag{79}$$

$$d\theta = \frac{v_{tan}}{r}\ [m/s] \tag{80}$$

$$d\,v_{rad} = \frac{v_{tan}^2}{r} + \frac{\delta\,Thr}{m} sin\alpha - \frac{GM}{r^2} - \frac{1}{2}\rho\,CD\,\sqrt{v_{rad}^2 + v_{tan}^2}\,A\,v_{rad}\ [m/s^2] \tag{81}$$

$$d\,v_{tan} = \frac{v_{rad}\,v_{tan}}{r} + \frac{\delta\,Thr}{m} cos\alpha - \frac{1}{2}\rho\,CD\,\sqrt{v_{rad}^2 + v_{tan}^2}\,A\,v_{tan}\ [m/s^2] \tag{82}$$

$$dm = -\frac{\delta\,Thr}{g0\,I_{sp}}\ [kg/s] \tag{83}$$

$$d\,\Delta v = I_{sp}\,g0 \ln\left(\frac{m}{m+dm}\right)\ [m/s^2] \tag{84}$$

$$d\,\Delta V_{drag} = \frac{Drag}{m}\ [m/s^2] \tag{85}$$

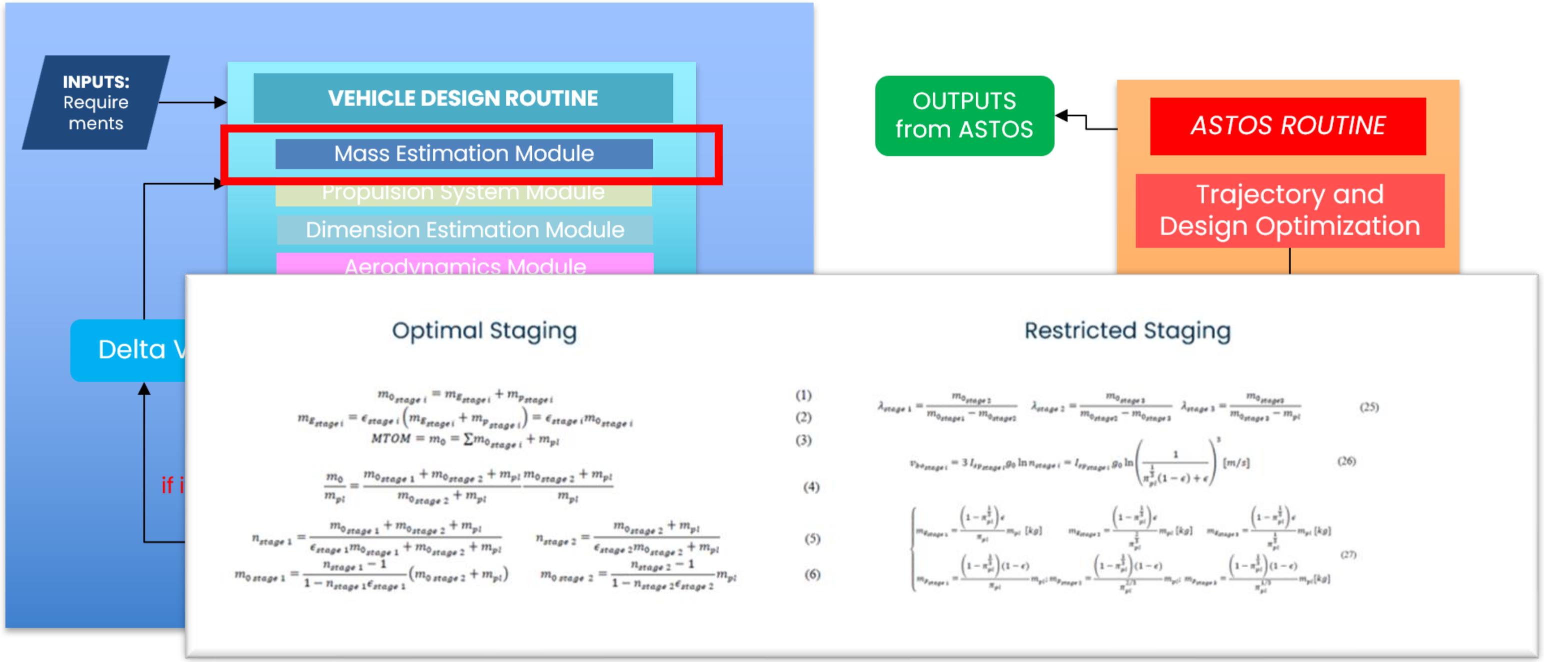
[5] O. Sutton and G. Biblarz, Rocket Propulsion Elements.
[6] F. Castellini, Multidisciplinary Design Optimization for expendable launch vehicles, 2012.
[7] R. Ernst, Liquid Rocket Analysis (LiRA). Development of a Liquid Bi-Propellant Rocket Engine.
[8] S. Contant, Design and Optimization of a Small Reusable Launch Vehicle Using Vertical Landing Techniques.
[9] F. Miranda, Design Optimization of Ground and Air-Launched Hybrid Rockets.
[10] R. V. Fernando de Souza Costa, “Preliminary Analysis of Hybrid Rockets for Launching Nanosats into LEO”.

Micro-Launcher Design Methodology

Mass Estimation Module -> **estimate the different masses** of the Launcher

Two Staging algorithms implemented.

1. ***Optimal Staging***
2. ***Restricted Staging***: simplified method (only for existing ML)
   -> MTOM is requested as input.



[2] H. Curtis, Orbital Mechanics for Engineering Students, Elsevier Aerospace Engineering Series, Elsevier, 2004.
[3] K. Suresh and B. Sivan, Integrated Design for Space Transportation Systems, Springer, 2015.
[4] D. M. Gaspar, "A Tool for Preliminary Design of Rockets".

Micro-Launcher Design Methodology

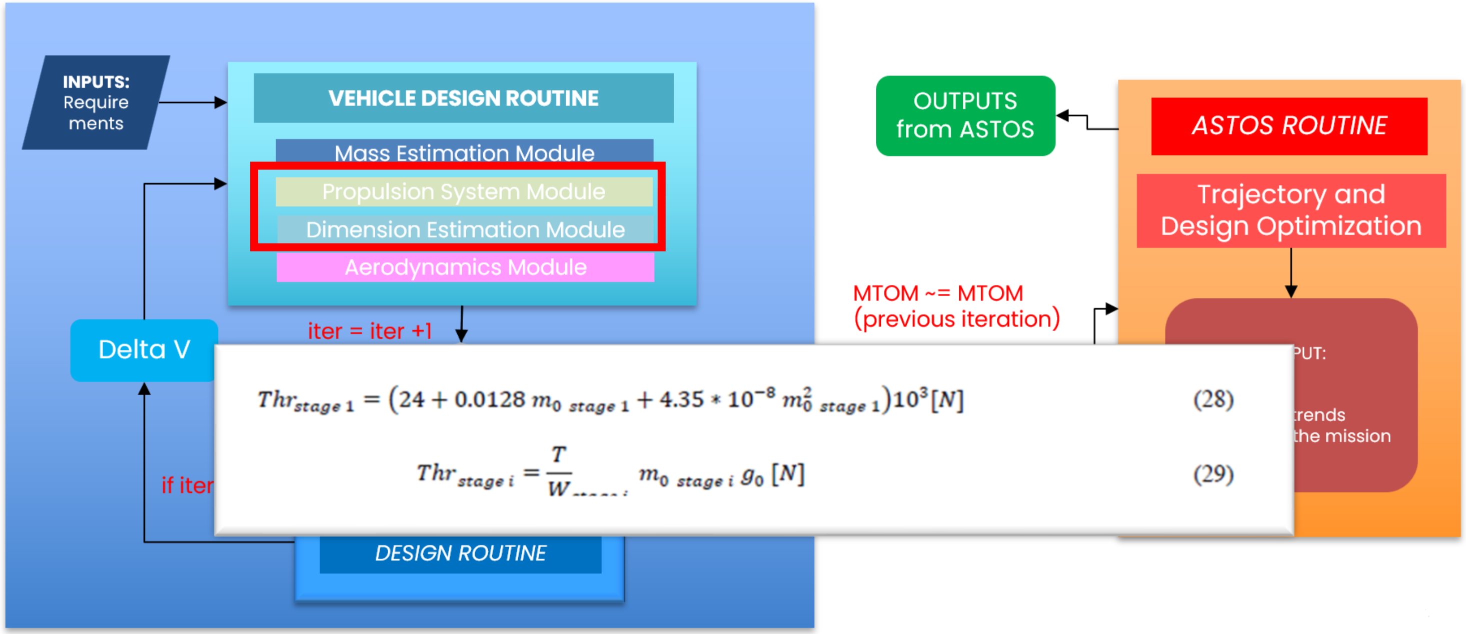
Propulsion System Module -> **Thrust** and **Geometrical characteristics** of the Engines.

Preloaded or **New propellant** in terms of:

1) Specific impulse;
2) Density;
3) Mixture Ratio (bi-propellant).

Dimensions Estimation Module -> **Geometrical characteristics** of the Launcher.

1) Tanks length;
2) Stages length;
3) Fairing length.



$$Thr_{stage\ 1} = (24 + 0.0128\ m_{0\ stage\ 1} + 4.35 * 10^{-8}\ m_{0\ stage\ 1}^2)10^3 [N] \tag{28}$$

$$Thr_{stage\ i} = \frac{T}{W_{stage\ i}}\ m_{0\ stage\ i}\ g_0\ [N] \tag{29}$$

[5] O. Sutton and G. Biblarz, Rocket Propulsion Elements.
[6] F. Castellini, Multidisciplinary Design Optimization for expendable launch vehicles, 2012.
[7] R. Ernst, Liquid Rocket Analysis (LiRA). Development of a Liquid Bi-Propellant Rocket Engine.
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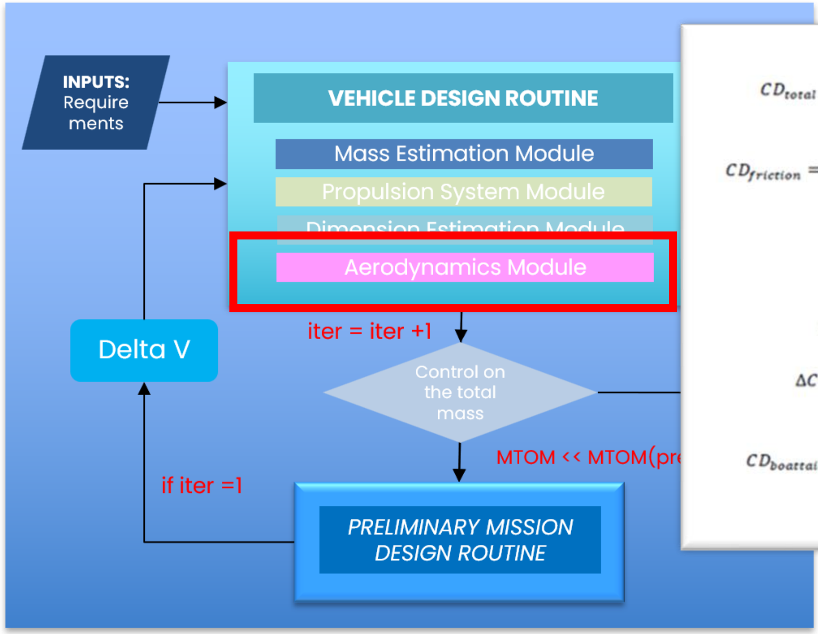
[10] R. V. Fernando de Souza Costa, "Preliminary Analysis of Hybrid Rockets for Launching Nanosats into LEO".

Micro-Launcher Design Methodology

Aerodynamics Module **->**
Drag coefficient = f (Mach, AoA).

Components considered:

1) **Base** Drag;
2) **Friction** Drag;
3) **Boattail** Drag;
4) **Supersonic** and **Transonic** Drag.



$$CD_{total} = CD_{friction} + CD_{base} + CD_{wave} + CD_{boattail} \quad (60)$$

$$CD_{friction} = C_f(final)\left[1 + \frac{60}{\left(\frac{L}{D}\right)^3} + 0.0025\left(\frac{L}{D}\right)\right] 4S_{base}/\pi D^2 \quad (61)$$

$$CD_{base}(M < 0.6) = \frac{K_{base}\left(\frac{D_{base}}{D}\right)^n}{\sqrt{CD_{friction}}} \quad (63)$$

$$\Delta Cd_{supersonic} = \begin{cases} \Delta C_{DMAX}F, if\ M \geq M_F \\ 0, if\ M < M_F \end{cases} \quad (72)$$

$$\Delta Cd_{transonic} = \begin{cases} \Delta C_{DMAX}F, if\ M_D \leq M \leq M_F \\ 0, if\ M < M_D\ or\ M > M_F \end{cases} \quad (71)$$

$$CD_{boattail} = \beta * \frac{A_{fore}}{A_{aft}} * CD_{base} * \begin{cases} 1\ \ if\ \sigma \leq 1 \\ \frac{3-\sigma}{2}\ \ if\ 1 < \sigma \leq 3 \\ 0\ \ if\ \sigma > 3 \end{cases} \quad (73)$$

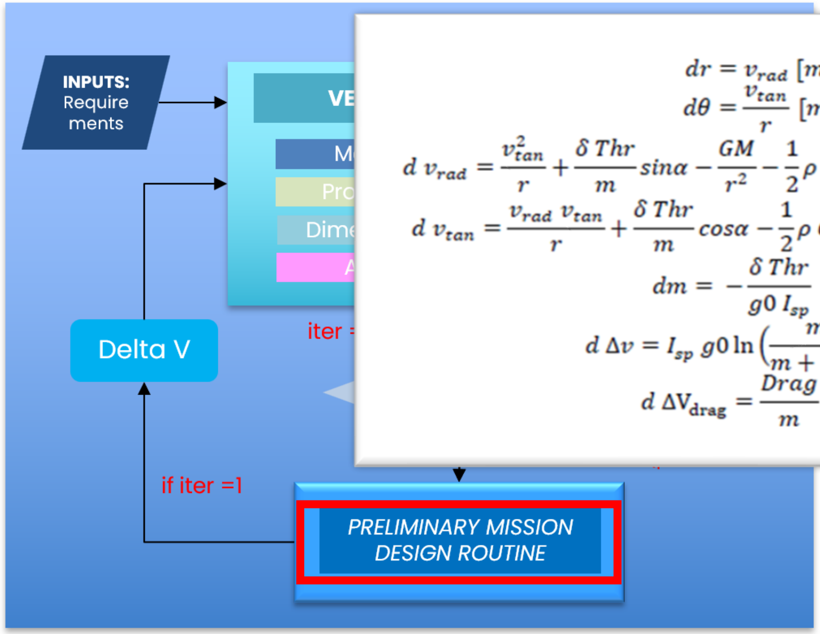
[11] P. Sharma, "Drag Coefficient Prediction".
[12] W. Stoney, "Collection of zero lift drag data on bodies of revolution from free flight investigation".

Micro-Launcher Design Methodology

Preliminary Mission Module ->

1) First trajectory estimation;
2) Variable trends throughout the mission;
3) **Delta V** and **Gravity** and **Drag Losses.**

Starting point for new iterations!



$$dr = v_{rad}\ [m/s] \tag{79}$$

$$d\theta = \frac{v_{tan}}{r}\ [m/s] \tag{80}$$

$$d\,v_{rad} = \frac{v_{tan}^2}{r} + \frac{\delta\,Thr}{m} sin\alpha - \frac{GM}{r^2} - \frac{1}{2}\rho\,CD\,\sqrt{v_{rad}^2 + v_{tan}^2}\,A\,v_{rad}\ [m/s^2] \tag{81}$$

$$d\,v_{tan} = \frac{v_{rad}\,v_{tan}}{r} + \frac{\delta\,Thr}{m} cos\alpha - \frac{1}{2}\rho\,CD\,\sqrt{v_{rad}^2 + v_{tan}^2}\,A\,v_{tan}\ [m/s^2] \tag{82}$$

$$dm = -\frac{\delta\,Thr}{g0\,I_{sp}}\ [kg/s] \tag{83}$$

$$d\,\Delta v = I_{sp}\,g0 \ln\left(\frac{m}{m+dm}\right)\ [m/s^2] \tag{84}$$

$$d\,\Delta V_{drag} = \frac{Drag}{m}\ [m/s^2] \tag{85}$$

[5] O. Sutton and G. Biblarz, Rocket Propulsion Elements.
[6] F. Castellini, Multidisciplinary Design Optimization for expendable launch vehicles, 2012.
[7] R. Ernst, Liquid Rocket Analysis (LiRA). Development of a Liquid Bi-Propellant Rocket Engine.
[8] S. Contant, Design and Optimization of a Small Reusable Launch Vehicle Using Vertical Landing Techniques.
[9] F. Miranda, Design Optimization of Ground and Air-Launched Hybrid Rockets.
[10] R. V. Fernando de Souza Costa, “Preliminary Analysis of Hybrid Rockets for Launching Nanosats into LEO”.

MicroLauncher Cost Estimation

Main Requirements

- ✓ i-DREAM shall support the **conceptual and preliminary design** of Microlaunchers (MLs) with the Life-cycle costing (LCC) assessment of MLs.

- ✓ This capability shall be exploitable:
  - inside the integrated framework (thus using inputs coming from design)
  - in standalone mode

Expected Tool Developments

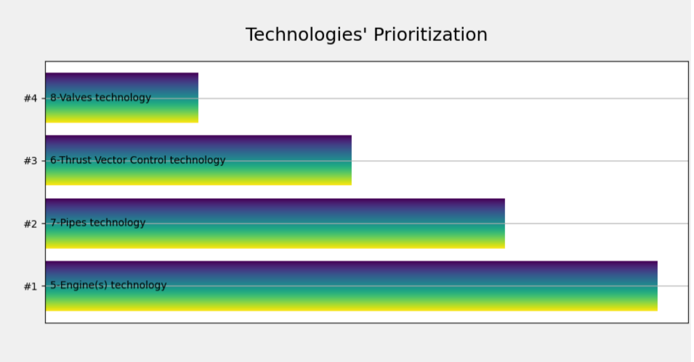
- ✓ Upgraded version of **HyCost**
  - HyCost is a proprietary tool of the research group of Politecnico di Torino, developed with ESA, to support a wide range of high-speed vehicles
  - TRIS has been validated for in different fields, from space exploration, to reusable access to space and re-entry vehicles.

- ✓ The cost estimation uses the heritage and know-how developed for previous contracts with ESA on the Microlaunchers design and evaluation capabilities.

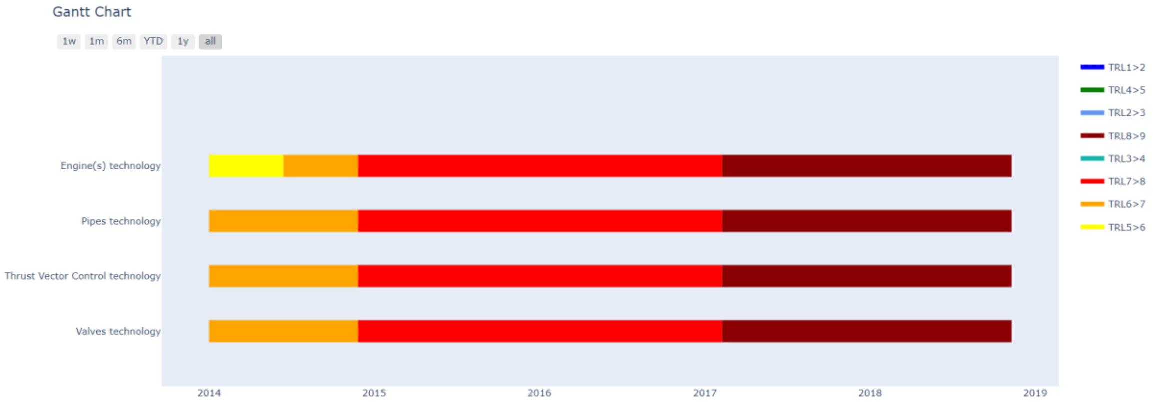
- ✓ The routine uses the collected data from previous contracts as available input for the "Existing" case.

MicroLauncher Technology Roadmapping – Outputs

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



Tech Name	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Engine(s) tech	01/01/2014	14/06/2014	26/11/2014	08/02/2017	10/11/2018
Pipes tech		01/01/2014	01/07/2014	05/12/2016	10/11/2018
TVC tech		01/01/2014	01/07/2014	05/12/2016	10/11/2018
Valves tech		01/01/2014	01/07/2014	05/12/2016	10/11/2018



MicroLauncher Technology Roadmapping – Inputs

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

Stakeholder	Role	Impact	Criterion	Prioritization Order
Rocket Lab	OP	KE	Current TRL	ASC
Rocket Lab	OP	KE	Cost at Completion	DESC
Rocket Lab	OP	KE	Number of Missions linked	ASC
Rocket Lab	OP	KE	Number of Activities linked	ASC
Rocket Lab	OP	KE	Number of BBs linked	ASC
Rocket Lab	OP	KE	Number of Ocs linked	ASC
PoliTo	E-U	MON	Current TRL	ASC
PoliTo	E-U	MON	Cost at Completion	DESC
NASA	C	KE	Cost at Completion	DESC
NASA	C	KE	Number of Missions linked	ASC
U.S. Government	SP	KS	Number of Missions linked	ASC
DARPA	S SP	KI	Cost at Completion	DESC
DARPA	SP	KI	Number of Missions linked	ASC
ESA	OP	KI	Cost at Completion	DESC
ESA	OP	KI	Current TRL	ASC

HLS Backup

Politecnico di Torino

1859

HLS Design and mission analysis methodology

Objective:

i-DREAM shall support the conceptual and preliminary design of HLSs and related nominal mission, while exploiting some routines of the commercial software **ASTOS**.

Tool:

- Upgraded version of **ASTRID-H** (Aircraft on-board Systems sizing and TRade-off analysis in Initial Design)
  - Proprietary tool of the research group of Politecnico di Torino
  - Developed for almost a decade through research activities.
  - ASTRID-H supports the conceptual and preliminary design of a wide-range of high-speed transportation system from supersonic/hypersonic civil aircraft to Reusable Access to Space.

Expected Outputs:

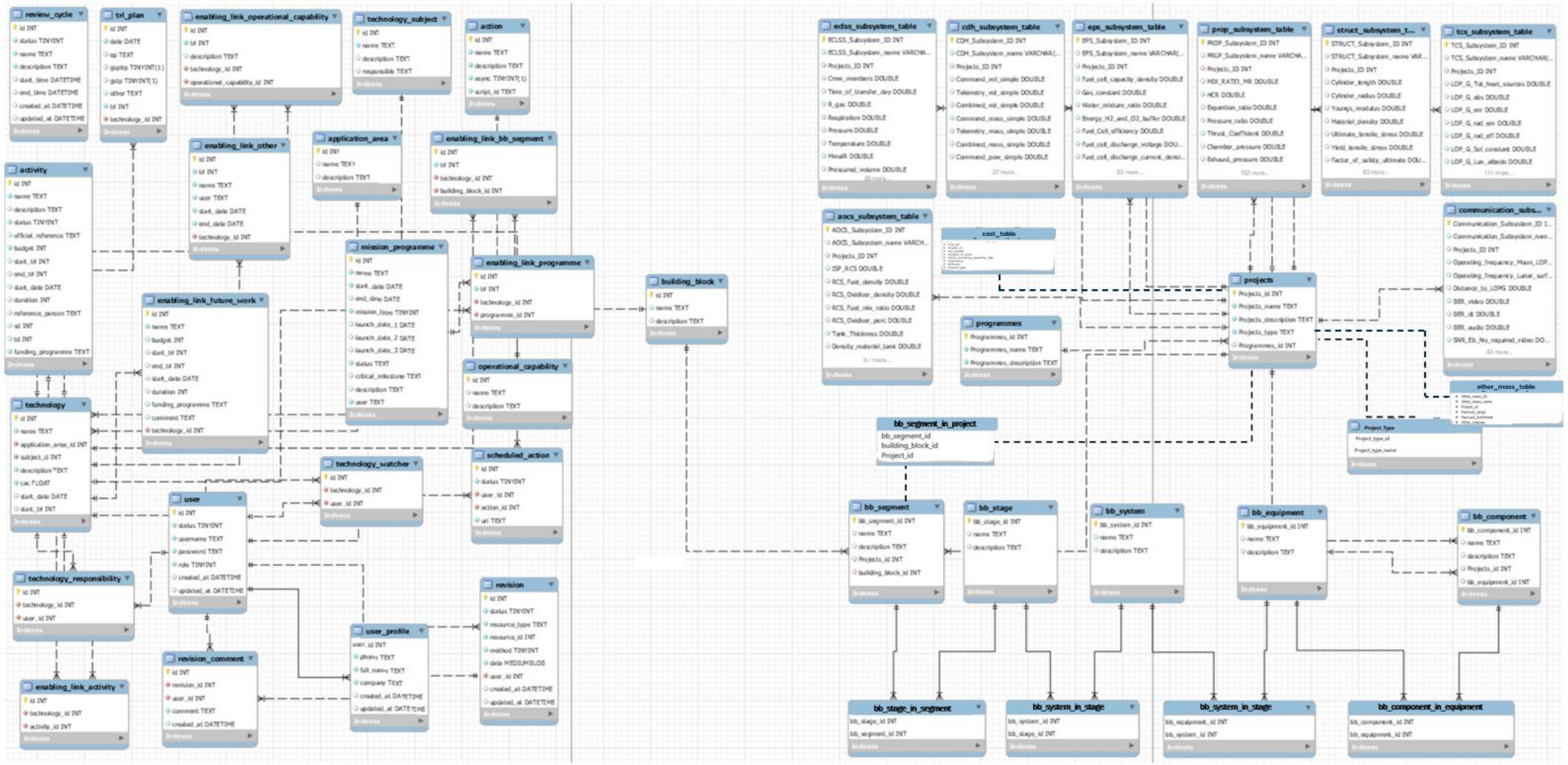
iASTRID-H for HLS shall enable two different types of analysis:
- Assessment and verification of an already existing HLS design (Existing routine) supported by TREX DB (ESA proprietary DB)
- Definition of a new HLS design and reference mission starting from a set of high-level requirements (New routine)

TREX Database

To support the multidisciplinary design of HLS, Politecnico di Torino upgraded **TREX**, a database initially developed by ESA to support internal technology roadmapping activities.

The MySQL version of TREx back-end has been properly modified to store data of existing HLS projects and to support:

- Design & mission analysis
- Cost Estimation
- Technology Roadmap



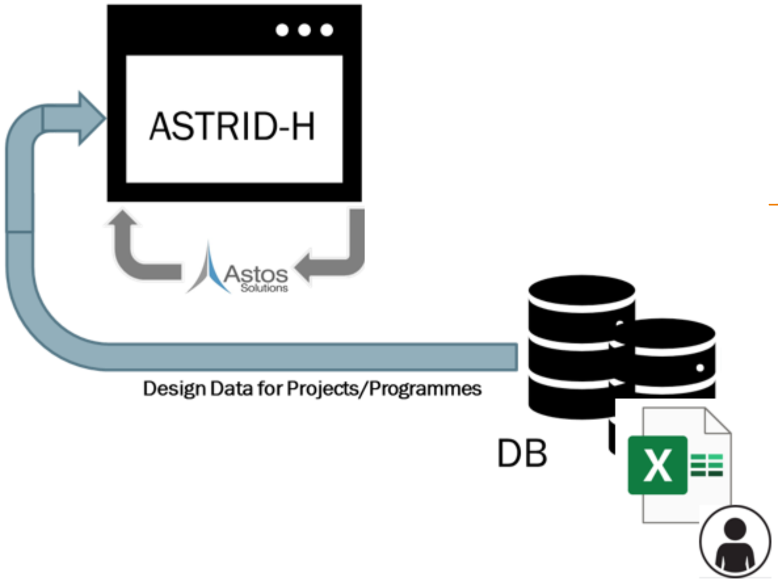
iDREAM (iASTRID-H) – HLS - Overview

Bottom-up approach:

- From subsystem to vehicle design

Inputs from **TREX** (or **User**):

- **Mission data** (estimated Delta Vs, mission phases time)
- Nominal **Payload Mass**
- Number of **crew**
- Total **mission time**
- Details on the **vehicle Configuration** (subsystems data: PROPULSION, ECLSS, COMM, CDH, AOCS, TCS, STR, EPS etc…)

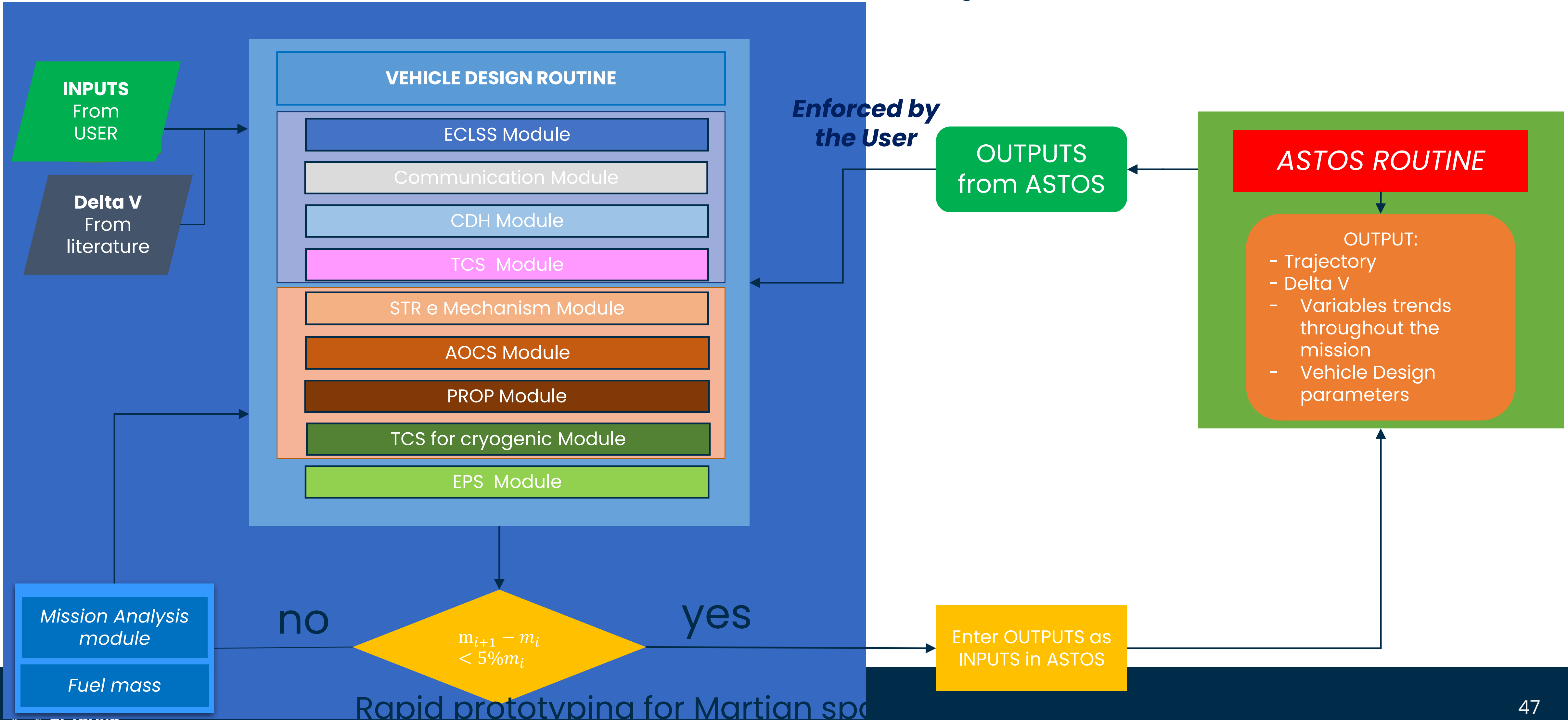


Outputs:

- **Vehicle geometry and Layout**
- **Vehicle performance (propellant mass, final DeltaV, mass budgets, power budgets)**
- **Mission Concepts**

iDREAM (iASTRID-H) - HLS – Design Steps

Human Landing System Design Routine –> Existing case



iDREAM (iASTRID-H) – HLS - Subsystems

ECLSS Module

Environment Control Life Support Subsystem (ECLSS) shall be able to sustain life for 4 astronauts during the mission.

TCS Module

Thermal Control Subsystem (TCS) shall be able to control temperature for human habitat ,and other subsystems' component. (MLI, louvres, heat pipes, coldplates, heaters)

AOCS Module

Attitude and Orbit Control Subsystem (AOCS) shall be able to sustain HLS asset along manoeuvres duration during the mission (AOCS fuel, tanks, AOCS engines, sun sensors, star trackers, etc…).

Communication Module

Communication shall be able to sustain communication between astronauts and LOPG orbit during the whole mission.

STR e Mechanism Module

Structure and Mechanism module estimates the mass, power and volume budgets of total structure, landing gear, docking mechanism and thermal protection system.

TCS for cryogenic Module

Thermal Control Subsystem (TCS) for cryogenic shall be able to control temperature for cryogenic fuel tanks.(MLI for fuel tanks)

CDH Module

Command and Data Handling(CDH) subsystem allows to interface human with other subsystems.

PROP Module

Propulsion Subsystem shall be able to sustain the descent manoeuvre during the mission. (fuel tanks, engine, pressurant and turbopumps)

EPS Module

Electrical Power Subsystem(EPS) shall be able to produce power required from the LSAM subsystems (batteries , solar arrays and fuel cells).

iDREAM (iASTRID-H) – HLS - Subsystems

Inputs:

- Number of Astronauts
- Mission Duration

$$m_{consumable} = 9.4 * n_{Crew} * n_{days} + 2.3 * n_{days} + 4.5 * n_{evacycles} \, [kg]$$

$$Air_{need} = Respiration_{data} *$$

$$V_{tot_{air}} = 7.772 * 10^{-}$$

$$V_{habitat} = n_{crew} * 20 *$$

$$m_{cabin} = 1.25 + 525 *$$

$$m_{tot_{ECLSS}} = m_{CO2_{scrubber}} + m_{Trace_{contaminant_{CS}}} + m_{Major}$$
$$+ m_{Avionics_{Air_{assembly}}} + m_{Intermoduel_{ventil}}$$
$$+ m_{fire_{exting}} + m_{N2_{tot_{withmarg}}} + m_{Ox_{tot_{w}}}$$
$$+ m_{tot_{O_2}} + +m_{cons} + m_{PCS} + mass_{OGA}$$
$$+ m_{gas_{reservoir}} \, [kg]$$

$$P_{tot_{ECLSS}} = P_{CO2_{scrubber}} + P_{Trace_{contaminant_{CS}}} + P_{Major}$$
$$+ P_{Avionics_{Air_{assembly}}} + P_{Intermoduel_{venti}}$$

$$V_{tot_{ECLSS}} = V_{CO2_{scrubber}} + V_{Major_{constituent_{analyzer}}} + V$$
$$+ V_{Intermoduel_{ventilation}} + V_{HEPA_{filter}} +$$
$$+ V_{reservoir_{tank}} + V_{inflatable_{airlock}} \, [$$

ECLSS main Data

	Value	[]
Crew_members	4	
n.Days	7	day
Habitat_vol	☑ 31.8	m3
num suit	1	
num EVA	1	
Suggested Values		
R gas	8.31	J/mol/K
Respiration	0.84	kg/p/day
Pressure	65500	Pa
Temperature	295	K
Mmair	28.965	g/mol
Pressured volume	31.8	m3
O2 concentration Vol	30	%
O2 molar mass	0.032	kg/mol
N2 Molar mass	0.028	kg/mol
N2 leakage	0	
num CO2 Scrubber (LiOH - based)	1	
num Trace Contaminant Control Subsystem (TCCS)	1	
num Major Constituent Analyzer (MCA)	1	

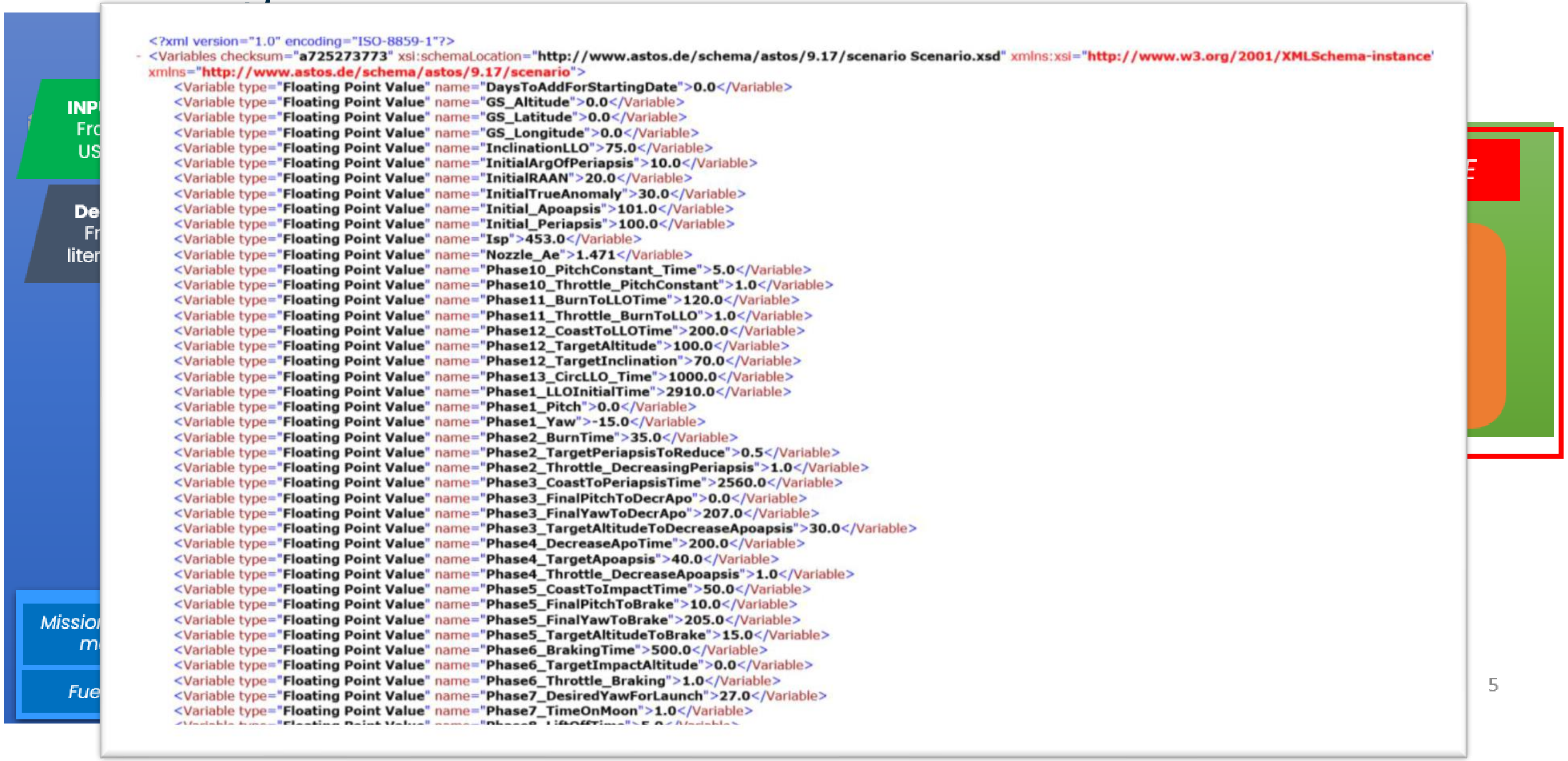
iDREAM (ASTOS) - HLS

Human Landing System Design Routine -> ASTOS Routine

ASTOS routine can be launched directly from iDREAM GUI.

Connection allowed thanks:

- IT collaboration
  - Connection GUI
- homotopy.xml file



```xml
<?xml version="1.0" encoding="ISO-8859-1"?>
- <Variables checksum="a725273773" xsi:schemaLocation="http://www.astos.de/schema/astos/9.17/scenario Scenario.xsd" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance'
xmlns="http://www.astos.de/schema/astos/9.17/scenario">
    <Variable type="Floating Point Value" name="DaysToAddForStartingDate">0.0</Variable>
    <Variable type="Floating Point Value" name="GS_Altitude">0.0</Variable>
    <Variable type="Floating Point Value" name="GS_Latitude">0.0</Variable>
    <Variable type="Floating Point Value" name="GS_Longitude">0.0</Variable>
    <Variable type="Floating Point Value" name="InclinationLLO">75.0</Variable>
    <Variable type="Floating Point Value" name="InitialArgOfPeriapsis">10.0</Variable>
    <Variable type="Floating Point Value" name="InitialRAAN">20.0</Variable>
    <Variable type="Floating Point Value" name="InitialTrueAnomaly">30.0</Variable>
    <Variable type="Floating Point Value" name="Initial_Apoapsis">101.0</Variable>
    <Variable type="Floating Point Value" name="Initial_Periapsis">100.0</Variable>
    <Variable type="Floating Point Value" name="Isp">453.0</Variable>
    <Variable type="Floating Point Value" name="Nozzle_Ae">1.471</Variable>
    <Variable type="Floating Point Value" name="Phase10_PitchConstant_Time">5.0</Variable>
    <Variable type="Floating Point Value" name="Phase10_Throttle_PitchConstant">1.0</Variable>
    <Variable type="Floating Point Value" name="Phase11_BurnToLLOTime">120.0</Variable>
    <Variable type="Floating Point Value" name="Phase11_Throttle_BurnToLLO">1.0</Variable>
    <Variable type="Floating Point Value" name="Phase12_CoastToLLOTime">200.0</Variable>
    <Variable type="Floating Point Value" name="Phase12_TargetAltitude">100.0</Variable>
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    <Variable type="Floating Point Value" name="Phase1_LLOInitialTime">2910.0</Variable>
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    <Variable type="Floating Point Value" name="Phase2_Throttle_DecreasingPeriapsis">1.0</Variable>
    <Variable type="Floating Point Value" name="Phase3_CoastToPeriapsisTime">2560.0</Variable>
    <Variable type="Floating Point Value" name="Phase3_FinalPitchToDecrApo">0.0</Variable>
    <Variable type="Floating Point Value" name="Phase3_FinalYawToDecrApo">207.0</Variable>
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```

iDREAM (iASTRID-H) - HLS

Human Landing System Design Routine -> Mission Analysis Routine

Mission Analysis

3 parts:

- **ASTOS: Descent** (with no Soft Landing Phase)
- Python environment: **Soft Landing Routine**
- **ASTOS: Ascent**

Descent phases:

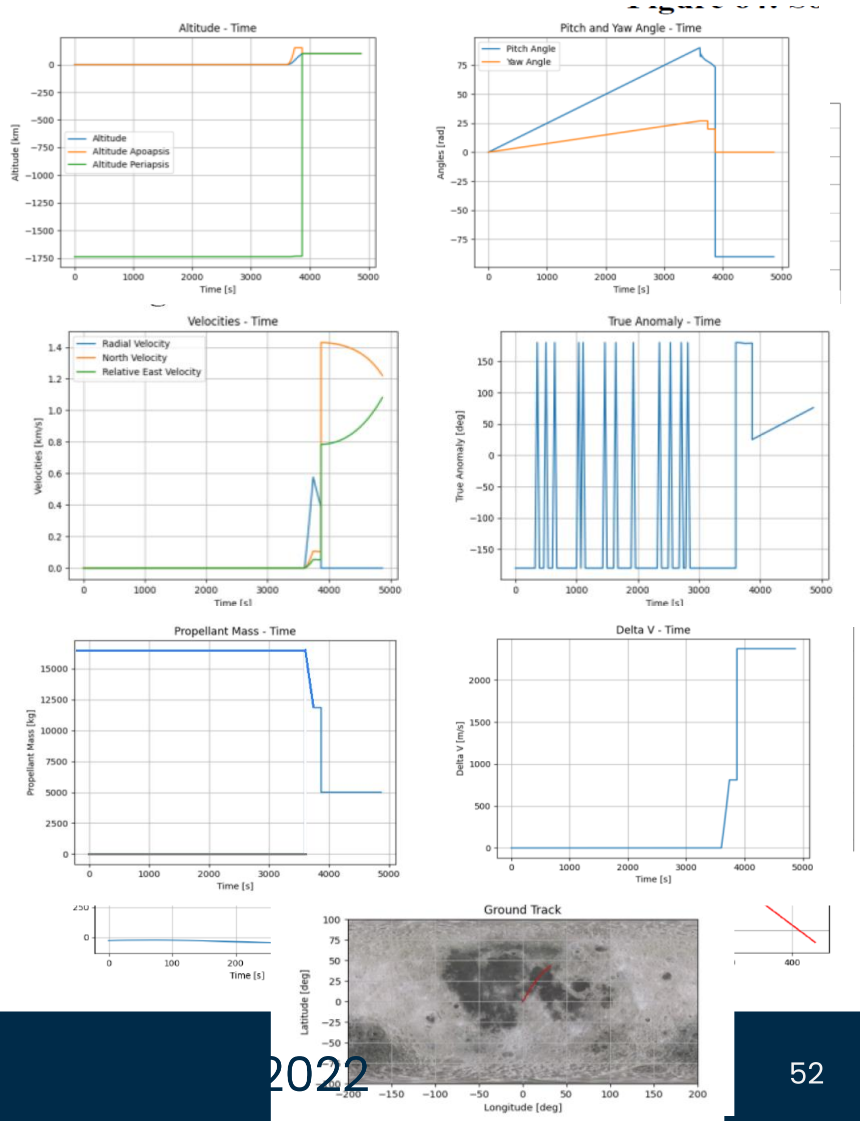
- **Phase 1**: orbiting the LLO
- **Phase 2**: beginning of the Descent phase, where there is the first burn in order to decrease the periapsis of the orbit
- **Phase 3**: target altitude [km] which enable the Phase end condition due to the new transfer orbit achieved through the previous burn
- **Phase 4**: once the desired altitude is reached, a second burn is used to decrease the apoapsis of the orbit
- **Phase 5**: coasting phase to decrease the altitude of the Lunar Lander

Soft Landing Routine:

Two dimensional dynamic model

- **Hypotheses:**
  - almost circular @ 15 km
  - Lander in the same plane of the Ground Station
  - Nobile

- **Phase 7**: HLS is landed on the moon
- **Phases 8-9-10**: ascent phase: the sequence of the phases is the typical one that is used for a vertical lift off of a rocket: Lift off, Pitch over and Pitch constant
- **Phases 11**: main burn during the ascent Phase: insertion of the vehicle in the transfer orbit to reach the desired altitude through the coasting phase
- **Phase 12**: coasting phase to reach the desired altitude
- **Phase 13**: Once the target altitude is reached, it is used a theoretical impulse to circularize the orbit



2022

Human Landing System - Cost Estimation

Objective:

The **second capability** of i-DREAM consists in supporting the conceptual and preliminary design of HLSs with the LCC assessment of HLSs.

Politecnico di Torino upgraded **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.

The AMCM model was implemented in the tool as cost routine for the HLS case. However, also a cost estimation methodology was developed based on analogy.

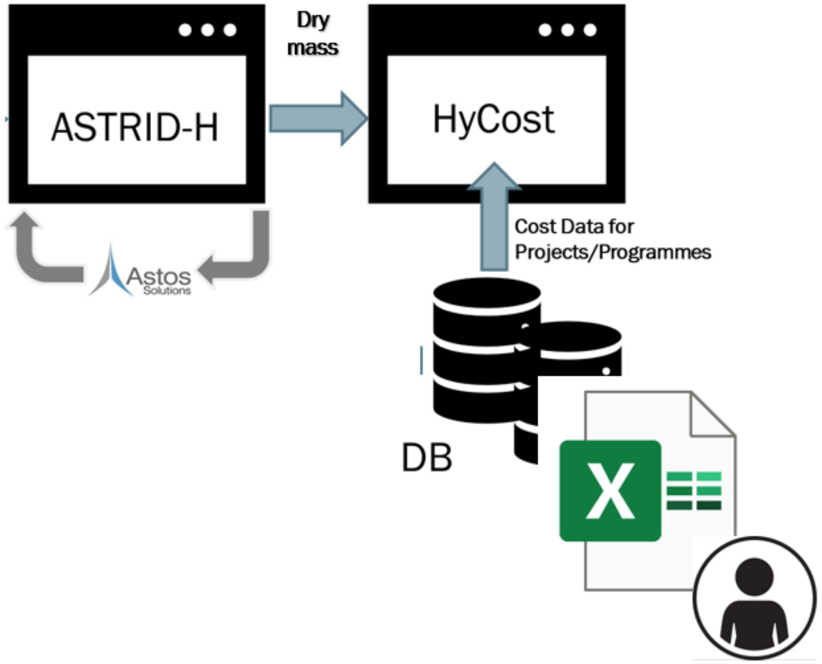
Human Landing System - Cost Estimation

Inputs from **TREX** (or **User**):

- **Number of units**
- **Initial Operating Capability year**
- **Inheritance**
- **Difficulty**
- **Mission Type**

Inputs from **iASTRID-H**:

- **Dry mass**



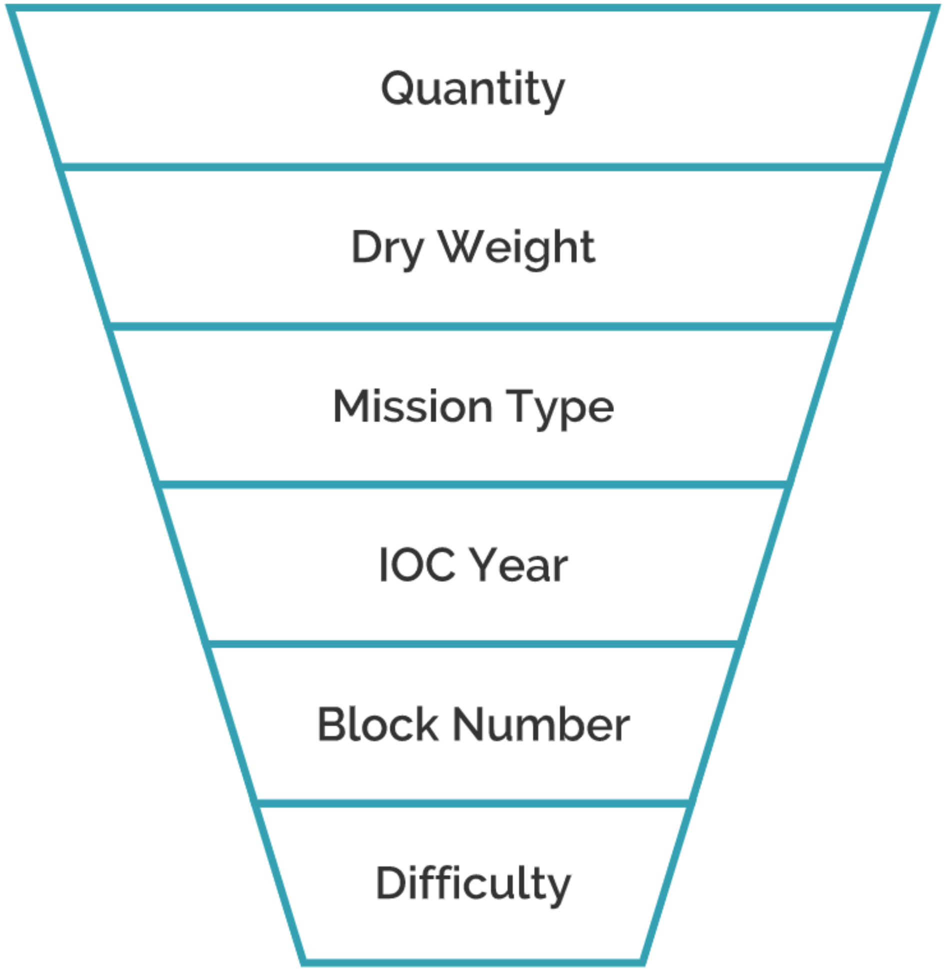
Outputs:

- **LCC assesment for HLSs**

Human Landing System - Cost Estimation

Integration of the AMCM

1. Input from GUI
2. Run estimation
3. Graph and print of results



Human Landing System - Cost Estimation - Validation

Analogy method cost estimation

- For early design stages with no consistent data available
- Based on attributes available for analogue missions.
- Evaluating the closeness of one project to another based on distance metrics

Mission	$FY2020M	Unit	Price	Crew	C	Target	T	GLOW [kg]	G	dry mass [kg]	M	∑
Apollo LM	23,413	15	*2,341**	2	0.40	Lunar Surface	0.0	16,374	0.07	4,920	0.21	0.17
Orion	29,500	12	*2,458**	4	0.00	Lunar Orbit	0.5	33,446	0.72	15,485	0.79	0.50
Crew Dragon	3,153		55mln/seat	7	0.60	LEO	1.0	12,055	0.28	6,350	0.07	0.49
Starliner	4,949		90mln/seat	7	0.60	LEO	1.0	13,000	0.23	5,591	0.14	0.49
HLS	*21,300*	*3*	*7100*	*4*		*Lunar Surface*		*17,975*		*7,150*		

Eulerian distance metric

k is the number of attributes/characteristics used for the adjustment, weighted as for α, normalised to measure the distance between the i-th and j-th projects.

$$d_{i,j} = \sqrt{\frac{\sum_k \alpha_k \left[\frac{x_k^i - x_k^j}{\max_i(x_k^i) - \min_i(x_k^i)}\right]^2}{\sum_k \alpha_k}}$$

Human Landing System - Cost Estimation - Validation

The budget allocated for the HLS in the Artemis program is

21,300 $FY2020M

The result of the cost estimation by analogy for the HLS is

18,619 $FY2020M

The result of the AMCM cost estimation is equal to

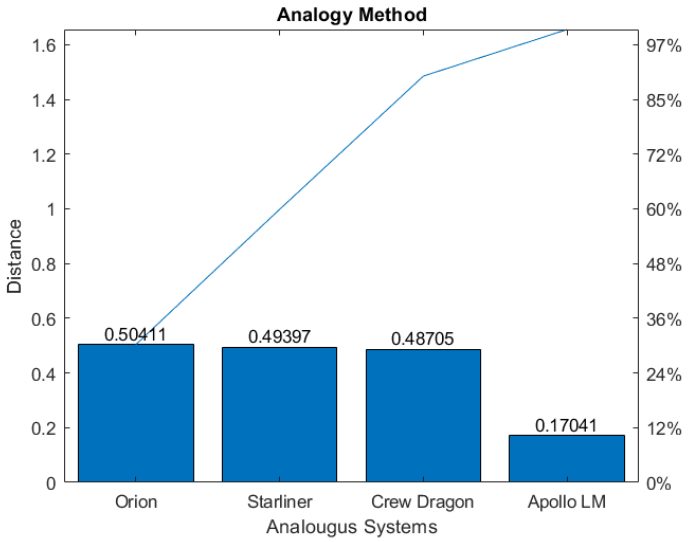
17,618 $FY2020M

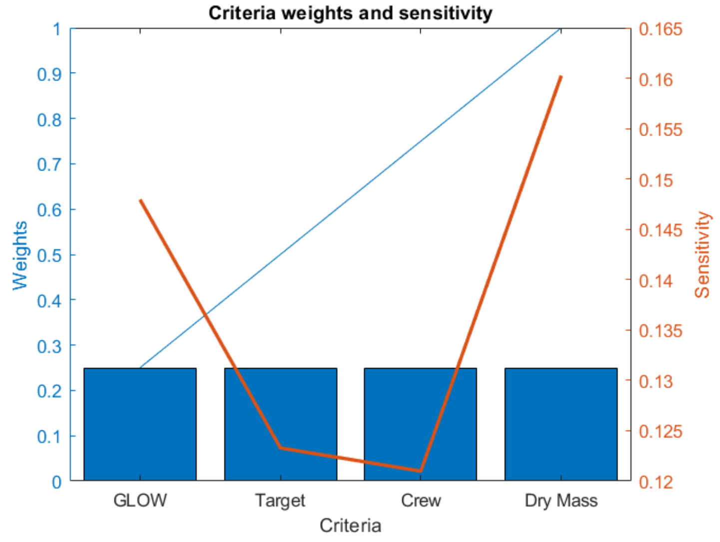
-14%

from the allocated budget

+5%

from the AMCM model





Mars Backup

Politecnico di Torino

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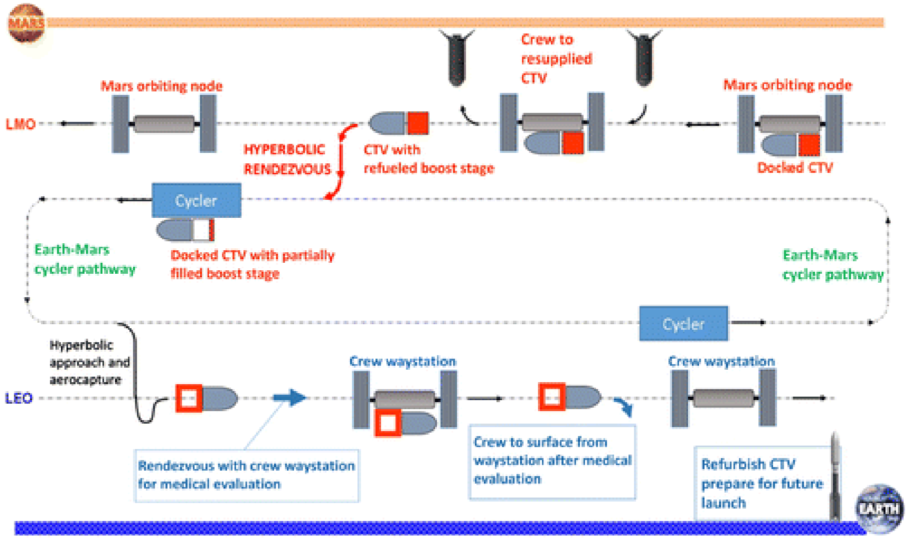
esa

- Let's say that the mission type is the one of a cycler. We would probably have:
  - A cycler
  - A crew transfer vehicle
  - A payload transfer vehicle (maybe)



Mission Type

Mission Element

N. crew, mission time

Crew capsule mass and volume

First estimation total mass

Propulsion System Mass Estimation

Propulsion System Preliminary Dimension Assessment

Initial Design Box

To refined design

- If we have a cycler mission and we focus on the transfer vehicle between Earth orbit and the cycler, we can reuse a lot of the work performed for Idream Moon.
  - ECLSS definition without including ECLSS
  - All the part related to chemical propulsion

ECLSS (i)

Inputs → number crew, mission time

M_crew = n_crew(70 kg + 42 kg) [70 kg – astronaut weight [1], 42 kg – suits weight [2]]

M_consumables [3] (modified because wrong)→

$$m_{\text{consumables}} = n_{\text{crew}}\ t_{\text{mission}}\left(2.9\frac{\text{kg}}{\text{day}}\left(1-\ 0.7\ \right)\right.$$
$$\left.+\,1.83\frac{\text{kg}}{\text{day}}+0.82\frac{\text{kg}}{\text{day}}+1.22\frac{\text{kg}}{\text{day}}\right)$$

[1] Hanford, A., “Advanced Life Support Baseline Values and Assumptions Document,” NASA TP-2015-218570, 2015.
[2] McMann, K. S. T., and Harold, J., US Spacesuits, Springer Praxis, Chichester, England, U.K., 2005, Chap. 4.
[3] Machado, Larissa Balestrero, and Markus Wilde. "Parametric design of a crew transfer vehicle for Earth–Mars cyclers." Journal of Spacecraft and

ECLSS (ii)

Inputs → number crew, mission time

Habitable Volume

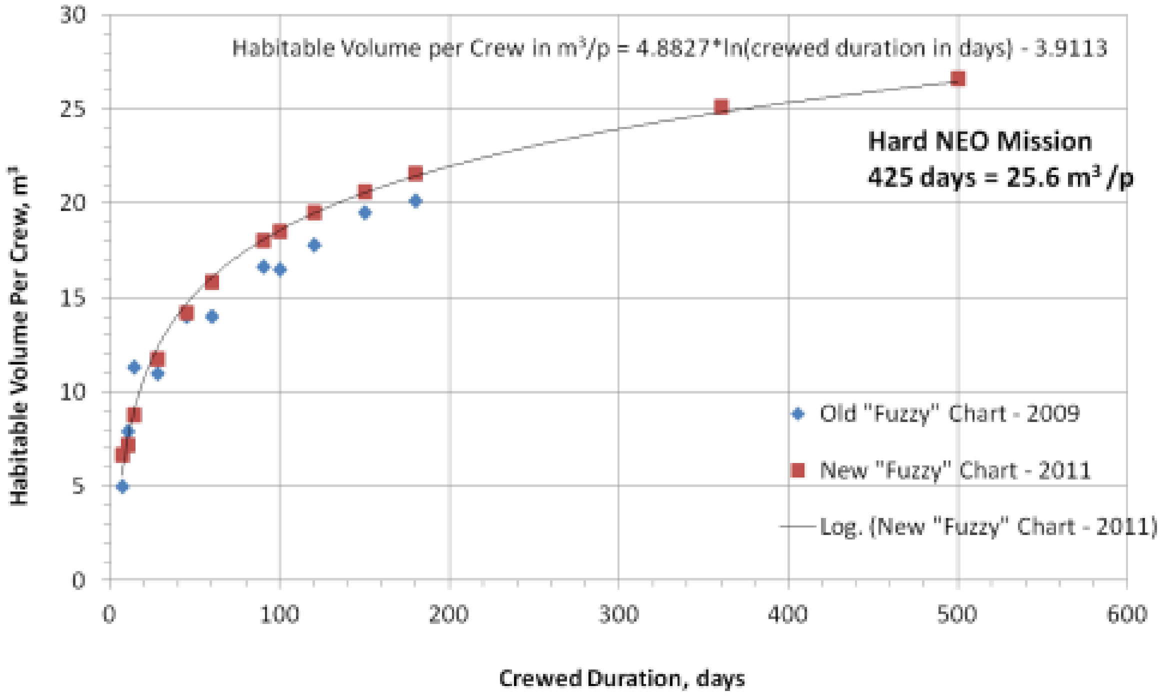


Figure 1: Averaged habitable volume curve.

[1] Simon, Matthew, et al. "Factors impacting habitable volume requirements: Results from the 2011 Habitable Volume Workshop." Center for Advanced Space Studies-Universities Space Research Association (2011).

ECLSS (iii)

Inputs → number crew, mission time

Crew Habitat Mass = From G. Drake ed., Mars Architecture Steering Group, 2nd Addendum of the Human Exploration of Mars, Design Reference Architecture 5.0, NASA Johnson Space Center, 2014. Or you can use the formula of Human Spaceflight to have a first estimate of the mass of the crew habitat. It keeps into account the pressurized volume as well!

From the study of other transfer vehicles it looks like the Crew Habitat Mass is around:

- 8%-12% of the total mass for a nuclear propelled system (To be refined)
- Around 20% for transfer vehicles toward a cycler (short travels)

Table 3. Mass of the habitable module (kg) as a function of the crew size and number of days, according to NASA data (NASA Design Reference Architecture, annex 2, 2014, page 370 [8]).

Crew size \ duration (d)	600	800	1000
3	23505	26794	30139
4	27128	31144	35199
6	34039	39694	45333

$$m_{bo} = 592 \times (\textit{number of crew} \times \textit{mission duration}\ [\mathrm{d}] \times \textit{pressurized volume}\ [\mathrm{m}^3])^{0.346} \quad (12\text{-}1)$$

ECLSS (iv)

Inputs → number crew, mission time

From human spaceflight the power associated to the crew habitat can be estimated as:

$$\textit{average power required} = 1000\text{ W} + 500\text{ W} \times \textit{number of crew}$$
$$\textit{peak power required} = \textit{average power} \times 1.75$$

- This value is around 5%-7% of the total required power for a transfer vehicle toward Mars (always from the book: Human Spaceflight)

Propulsion System Sizing - Chemical

Estimate thrust level from the initial calculate weight (T/W = 1.5/2)

Estimate number of Thrusters given an engine thrust from database (same as IDREAM standard) or estimate mass Thruster from the IDREAM regression formulae (the one that Giuseppe Narducci built for different types of propulsion systems).

Estimate the tanks and engine length and diameter following what Giuseppe Narducci did.

You can have chemical propulsion if you use a cycler → you just

IDREAM Regression Propulsion – Chemical

$$m_{engine}\,(Turbo-pump) = \begin{cases} 7.54354\,e-3\,Thr^{0.885635} + 20.2881\ for\ cryo\ propellant\ (Thr \leq 200e3) \\ 1.9101\,e-3\,Thr\ for\ cryo\ propellant\ (Thr > 200e3) \\ 3.75407e3\,Thr^{0.0705627} - 8.8479e3\ \ for\ cryo\ storable\ propellant\ (Thr \geq 450e3) \\ -0.0003\left(\frac{Thr}{1000}\right)^2 + 1.3807\left(\frac{Thr}{1000}\right) for\ cryo\ storable\ propellant\ (Thr < 450e3) \\ 6.37913Thr^{0.353665} - 148.832\ for\ storable\ propellant\ (Thr \geq 200e3) \\ -0.0021\left(\frac{Thr}{1000}\right)^2 + 2.0264\left(\frac{Thr}{1000}\right) for\ storable\ propellant\ (Thr < 200e3) \end{cases} [kg] \tag{35}$$

$$m_{engine}\,(Pressure-Fed) = \begin{cases} -2.13325e-9\,Thr^2 + 1.7087e-3\,Thr + 6.38629\ for\ cryo\ storable\ propellant\ (Thr \geq 300e3) \\ -0.0005\left(\frac{Thr}{1000}\right)^2 + 1.244\left(\frac{Thr}{1000}\right) + 18.336\ for\ cryo\ storable\ propellant\ (Thr < 300e3) \\ -3.36532e-8\,Thr^2 + 4.74402e-3\,Thr - 19.3920\ for\ storable\ propellant\ (Thr < 55e3) \\ 25.56\log\left(\frac{Thr}{1000}\right) + 29.824\ for\ storable\ propellant\ (Thr \geq 55e3) \end{cases} [kg]$$

The total mass of the engine can be evaluated as in [6] using eq. (36):

$$m_{engine\ TOT} = n_{engine} m_{engine}\ [kg] \tag{36}$$

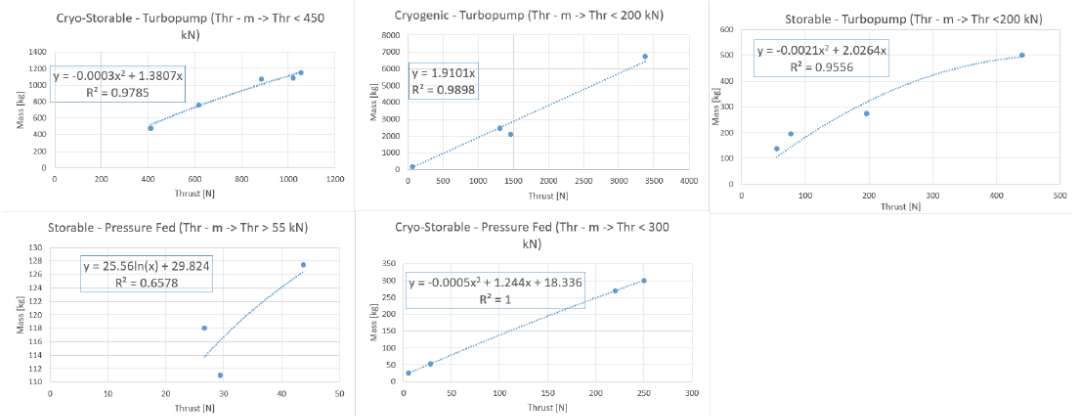


Figure 5: MERs for Engine mass (LRE).

IDREAM Regression Propulsion – Chemical

$$\begin{cases} m_{press} = 1.1 \dfrac{p_{tank} \cdot 10^5 (V_F + V_{ox})}{R\, T_{press}} \cdot \dfrac{\gamma}{1 - p_{tank}/p_{press}} \; [kg] \\ m_{press_{tank}} = 4\,\pi \left(D_{press}\right)^2 \tau_{press} \rho_{tank} \; [kg] \end{cases}$$

$$m_{press_{sys}} = m_{pressurant} + m_{press_{tank}} \; [kg]$$

$$\begin{cases} m_{tank}(bi - prop) = m_{tank_{ox}} + m_{tank_F} \begin{cases} m_{tank_{ox}} = 1.2 \cdot \dfrac{\frac{\rho_{tank_{ox}} \pi}{6} \left({D_{rocket}}^3 - (D_{rocket} - 2\tau_{tank})^3\right)}{\pi (D_{rocket} - 2\tau_{tank})^2} \\ \quad +1.5 \left(\left(\frac{D_{rocket}}{2}\right)^2 - \left(\frac{D_{rocket}}{2} - \tau_{tank}\right)^2 \right) L_{tank_{ox_{cyl}}} \\ m_{tank_{fuel}} = 1.2 \cdot \dfrac{\frac{\rho_{tank_F} \pi}{6} \left({D_{rocket}}^3 - (D_{rocket} - 2\tau_{tank})^3\right)}{\pi (D_{rocket} - 2\tau_{tank})^2} \\ \quad +1.5 \left(\left(\frac{D_{rocket}}{2}\right)^2 - \left(\frac{D_{rocket}}{2} - \tau_{tank}\right)^2 \right) L_{tank_{F_{cyl}}} \end{cases} \\ m_{tank}(mono) = m_{tank} = 1.2 \cdot \dfrac{\frac{\rho_{tank} \pi}{6} \left({D_{rocket}}^3 - (D_{rocket} - 2\tau_{tank})^3\right)}{\pi (D_{rocket} - 2\tau_{tank})^2} \\ \quad +1.5 \left(\left(\frac{D_{rocket}}{2}\right)^2 - \left(\frac{D_{rocket}}{2} - \tau_{tank}\right)^2 \right) L_{tank_{cyl}} \end{cases} \qquad (40)$$

$$L_{tank} = \begin{cases} \left(\dfrac{m_{ox}}{\rho_{ox}} + \dfrac{m_F}{\rho_F} + \dfrac{\pi}{6}\right) \dfrac{(1 + V_{ullage})4}{\pi \quad D_{tank}^2} & if\ bi - prop \\ \dfrac{m_{mono}}{\rho_{mono}} \dfrac{(1 + V_{ullage})4}{\pi \quad D_{tank}^2} & if\ mono \end{cases} \quad [m]$$

$$L_{intertank} = 0.3 \cdot r_{rocket} \; [m]$$

$$m_{intertank} = \begin{cases} 5.4015 \cdot 2\pi r_{rocket} L_{intertank} \left(3.2808 (2\, r_{rocket})\right)^{0.5169} \rightarrow lower\ stage \\ 3.8664 \cdot 2\pi r_{rocket} L_{intertank} \left(3.2808 (2\, r_{rocket})\right)^{0.6025} \rightarrow upper\ stages \end{cases} \; [kg]$$

Take at home lesson: for most of the propulsion subsystem we can use what is already in IDREAM

IDREAM Regression Propulsion – Chemical

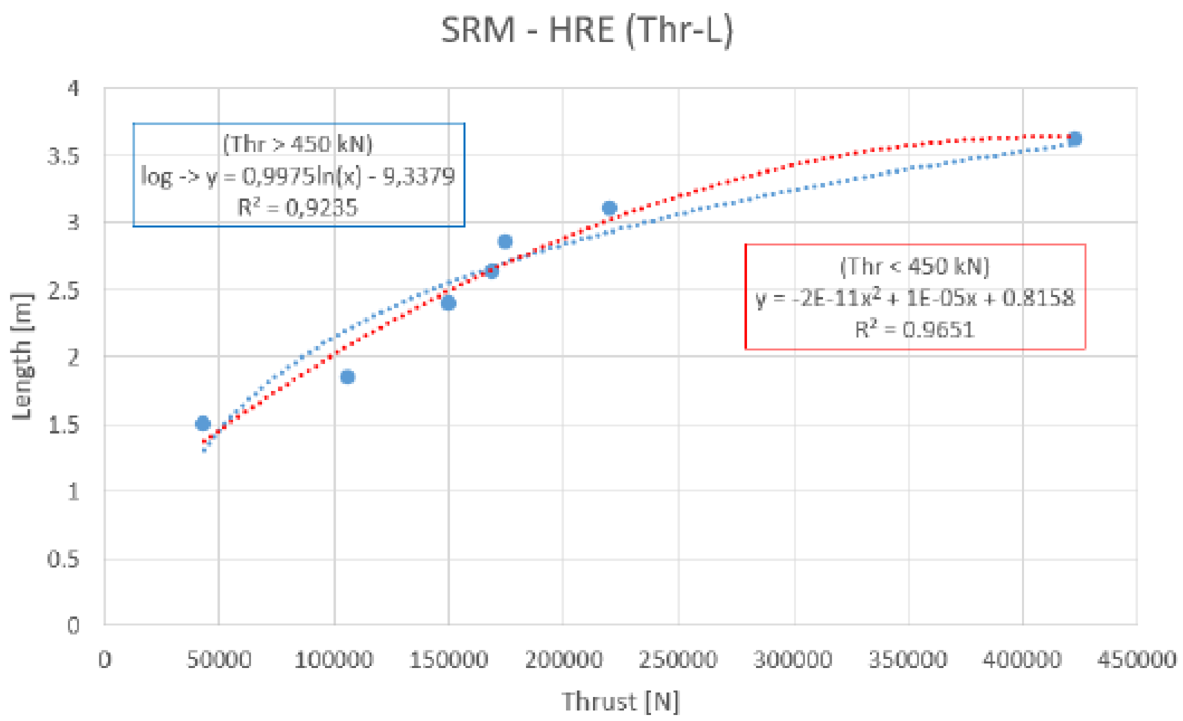


Figure 9: SRM - HRE Regression law Thrust [N]-Length [m]

Take at home lesson: for most of the propulsion subsystem we can use what is already in IDREAM

Propulsion System Sizing Beyond Idream - Chemical

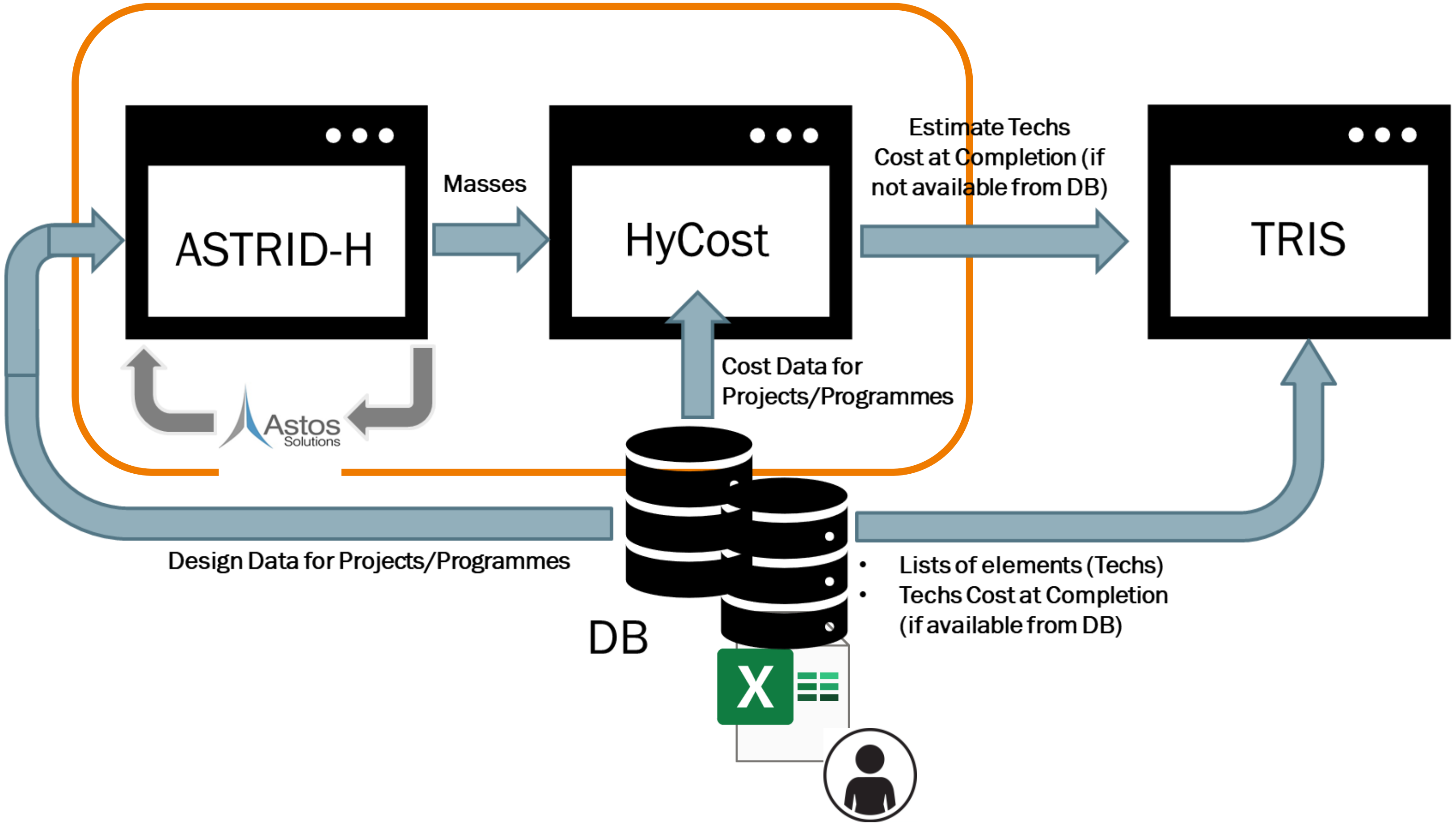
Propulsion system mass of valves, lines structure from [1]

$$m_{valves,lines,structure} = \left(\frac{27}{73}\right) * \left(m_{engine} + m_{tanks} + m_{intertank}\right)$$

You have an itertank if your tank is not spherical

[1] Machado, Larissa Balestrero, and Markus Wilde. "Parametric design of a crew transfer vehicle for Earth–Mars cyclers." Journal of Spacecraft and Rockets 57.3 (2020): 565-579.

iDREAM for Mars



DESIGN

1. Propulsion
   i. Nuclear
2. ECLSS
   i. Lower in %mass
   ii. Artificial gravity

COST

1. AMCM
2. Analogy method