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A methodology to support strategic decisions in future human space exploration: from scenario definition to building blocks assessment.

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The human exploration of multiple deep space destinations (e.g. Cis-lunar, NEAs), in view of the final challenge of sending astronauts to Mars, represents a current and consistent study domain especially in terms of its possible scenarios and mission architectures assessments, as proved by the numerous on-going activities about this topic and moreover by the Global Exploration Roadmap. After exploring and analysing different possible solutions to identify the most flexible path, a detailed characterization of several Design Reference Missions (DRM) represents a necessity in order to evaluate the feasibility and affordability of deep space exploration missions, specifically in terms of enabling technological capabilities.

The study presented in this paper was aimed at defining an evolutionary scenario for Deep Space Exploration in the next 30 years with the final goal of sending astronauts on the surface of Mars by the end of 2030 decade. Different destinations were considered as targets to build the Human Exploration Scenario, with particular attention to Earth-Moon Lagrangian points, NEA and Moon. For all the destinations selected as part of the exploration scenario, the assessment and characterization of the relative Design Reference Missions was performed. Specifically they were defined in terms of strategies, architectures and mission elements. All the analyses were based on a pure technical approach with the objective of evaluating the feasibility of a long term strategy for capabilities achievement and technological development to enable future space exploration.

The paper describes the process that was followed within the study, focusing on the adopted methodology, and reports the major obtained results, in terms of scenario and mission analysis.

Keywords: human space exploration; scenario; design reference mission.

1. Introduction

The next step in the Human Space Exploration (HSE) is to travel beyond Low Earth Orbit (LEO), and in this regard numerous activities are being carried out by the major space agencies, industries and academia trying to assess the best path to be followed in the exploration of the solar system, with the final objective of a human mission to Mars and through multiple deep space destinations intermediate human missions (e.g. Near Earth Asteroids). Examples of this type of study can be found in [1, 2, 3, 4].

The most significant reference study is the Global Exploration Roadmap [3, 5, 6, 7] whose latest version identifies two possible alternative paths, "Asteroid Next" and "Moon Next", providing a general preliminary description of the strategy to be followed.

According to the current scientific community interest in the analysis of future scenarios of exploration, a research activity, involving the Aerospace Systems Engineering groups of Politecnico di Torino (Italy) and Massachusetts Institute of Technology (USA) with the support of Thales Alenia Space-Italy as industrial partner (MITOR 2012 project), was carried out in 2012. This research focused on the Human Space Exploration topic, from the definition of a possible scenario, with the assessment of the missions, both humans and robotics, up to the identification of the enabling technologies [8][1].

It is very important to establish a specific roadmap defining the steps to be followed in the exploration of solar system: it represents the first step where to start from for detailed analyses at missions and building blocks assessment.

The study started from the identification and analysis of feasible evolutionary scenarios for Deep Space Exploration. Different destinations were considered as targets and a reference scenario was built on the basis of a "capabilities analysis". In the frame of the selected scenario Design Reference Missions (DRM) were

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[1] The results of the study are collected in the report: "Human Space Exploration: from Scenario to Technologies – MITOR Project 2012 Final Report", M.A. Viscio, A. Messidoro September 2012, Unpublished Results

characterized in terms of architecture and mission elements, as well as of the subsystems composing them[2]. A detailed investigation of the DRM architecture is necessary in order to select the most interesting solution, and in this regard several architecture techniques are under study/development. For instance, the Space System Architecture Group of the MIT AeroAstro Department is dealing with this topic [10].

Successively, the critical subsystems and the relevant key technologies were investigated. They shall enable the DRMs and support the whole scenario.

The paper describes the methodology that was developed and adopted to build the HSE reference scenario and reports the major obtained results (in terms of human exploration scenario and mission analysis). The various steps of the process are discussed in details; however only some example cases are reported, in order to allow a clearer understanding.

2. Human Space Exploration Scenario

The HSE scenario analysed in the frame of the MITOR 2012 project was built considering as final goal a human mission to Mars by the end of the 2030 decade.

In particular the NASA DRA 5.0 was taken as reference mission [11]. This study was selected as reference among several others [12, 13, 14, 15, 16, 17, 18] mainly due to the completeness and accuracy of the available data.

Although the mission as described by NASA DRA 5.0 is quite ambitious and has several weak points in its definition, all the considerations done within this study could be easily extended to other mission opportunities, which envisage Mars Human mission as final target.

As also addressed in [11], the complexity and costs associated to this type of mission would be very high, thus limiting the probability to accomplish such a mission by the end of 2030s. However, unlike the NASA DRA 5.0 mission (focusing on a direct mission to Mars), the idea behind the present study is that of following a gradual path in the expansion through the solar system, which can allow a stepwise technological development and capabilities achievement that can drastically reduce the risks and costs associated to a mission like the NASA DRA 5.0, making it a more realistic opportunity.

The objective of this study was to demonstrate the importance and feasibility of developing a long-term strategy for capability evolution and technology development, when considering space exploration, and specifically to provide a general methodology to be followed in the assessment of a reference scenario. According to this, even if a different “easier” architecture (e.g. with a small number of crewmembers [16, 17, 18]) or a different time opportunity (maybe a postponed time opportunity), were considered for the final mission to Mars, the considerations done in this study, and most of all the methodology developed, would still be valid and applicable. More in general, the developed methodology can be considered versatile and theoretically practicable in case the overall scenario is shifted in time, due to delays in the development of specific technologies or to available missions’ opportunities.

To build up the HSE scenario, the first step was characterized by the identification of the intermediate destinations concepts that most efficiently allow demonstrating the capabilities required for the reference human mission to Mars. All the study was based on a pure technical/performance approach, with no risk and cost analyses, as well as no political considerations: the driving criterion for the scenario definition was given by the capabilities required for the final reference mission to Mars.

For the selected destination concepts the most evolutionary strategies, missions, architectures and elements to be implemented to incrementally move towards the first human mission to Mars, were analysed.

A schematic diagram showing the work flow that was followed for the definition of the HSE Scenario is reported in figure 1.

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[2] A methodology that was considered as reference is described in [9].

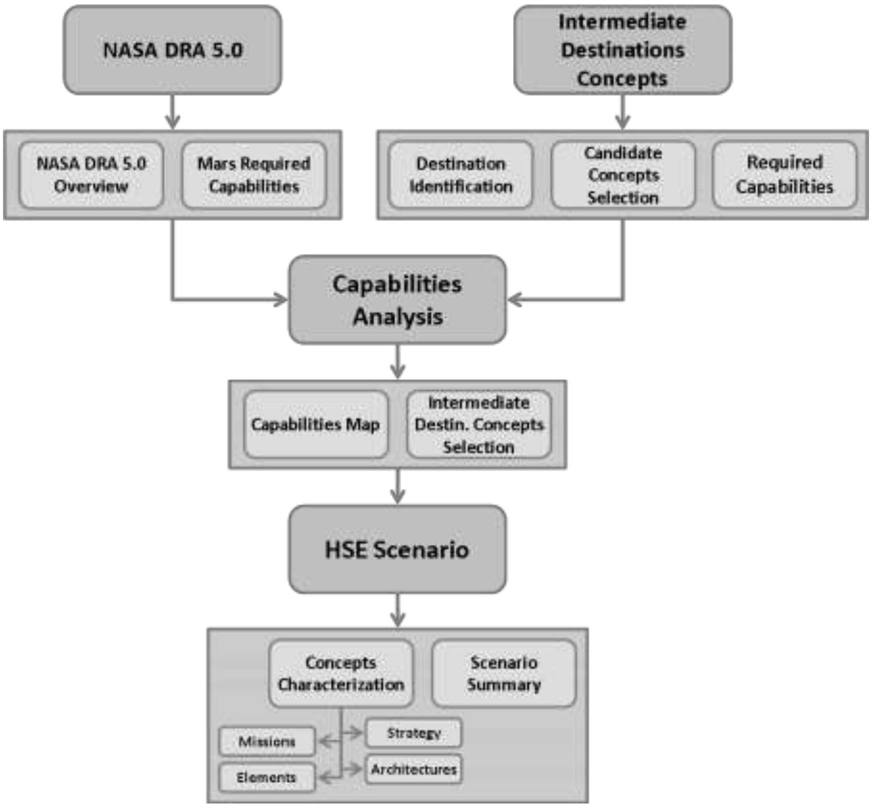

Fig. 1: Work Flow.

An overview of the NASA DRA 5.0 reference mission was necessary to identify the needed capabilities to accomplish that mission. A "capability" is basically a function that is likely to be implemented in a subsystem of an element.

The other branch of the diagram of figure 1 refers to the analysis of the intermediate destinations to be included in the scenario. Firstly several possible destinations were identified and for them alternative "candidate concepts" were defined. For all the candidate concepts a list of capabilities was derived, starting from those required for Mars.

At this point, combining the list of capabilities needed for Mars and for all the other destinations candidate concepts, a global capabilities map was built. Looking at this capabilities map, a down selection of a limited number of intermediate destinations concepts was performed, in order to reduce and simplify the overall scenario.

Once the intermediate destinations concepts had been selected, a quite detailed characterization of all the missions to be part of the scenario was done, in terms of strategy, missions, architectures and elements.

The final result is an overall scenario of exploration, which includes many missions, both human and robotic, which are conceived to allow a gradual implementation and achievement of the capabilities required to accomplish the reference human mission to Mars by the end of 2030s, according to NASA DRA5.0.

In the following sections the various steps are described in details and some examples are discussed.

2.1. Reference Human Mission to Mars

In this section a brief summary of the main features of the NASA DRA 5.0 is reported to better understand what will be discussed later on in the paper (For additional details refer to [11]).

The main reasons why the NASA DRA 5.0 was taken as reference for the present study were:

- the level of completeness of the work with detailed considerations also on elements, subsystems and technologies,
- the accuracy of the analysis supporting main trade-offs decisions and of justifications where only a qualitative assessment was performed.

The major mission attributes and high-level key decisions are reported in table I.

Attributes/Key-decisions	Value
Timeframe	2035-2040
Mission duration	5 years
Mission type	Conjunction
Cargo pre-deployment	Yes
Mars Capture Method	Cargo: Aerocapture Crew: Propulsive
ISRU	Yes – LOX for ascent
In-space propulsion	Nuclear Thermal
Number of crew members	6 – all on surface
Surface exploration strategy	Commuter
Total IMLEO Mass	848 t
Total Launches	9
Crew Mission Durations – days	
LEO	5
Outbound Cruise	174
Mars Orbit	20
Mars Surface	539
Inbound Cruise	201
Total – Deep Space	395
Total – Mission	939

Table I: NASA DRA 5.0 Mission attributes and key decisions

The NASA DRA 5.0 foresees two cargo missions to Mars in 2037:

- the first one is envisioned to pre-deploy assets on the surface, such as power plants, mobility, utility and communications elements, ISRU plant and the Mars Ascent Vehicle (MAV);
- the second one is envisaged to insert into a 1-sol Mars orbit the manned lander and the surface habitat, carrying also pressurized rovers for additional surface mobility capabilities.

The crew mission is planned to start two years later, given that all the LOX propellant needed for the ascent has been produced and stored in the MAV tanks.

The human mission includes the following phases: spacecraft assembly in LEO, outbound transfer, Mars orbit insertion, transfer of the crew to the manned lander, Mars entry, descent and landing, operations on the surface, ascent, rendezvous with the main orbiting S/C, inbound transfer and Earth direct re-entry.

In order to accomplish all these phases and the required functions a total of 28 different elements, belonging to transportation, surface and in-space categories, are estimated to be required by NASA engineers with their specific concepts of operations, design drivers, functions to be accomplished and technologies to be implemented. An overview of which are these 28 elements is shown in figure 2 (the number of units for each element is indicated as well).

Fig. 2: Mars required elements.

For this reference human mission to Mars an analysis of the needed capabilities was performed. The identified capabilities were listed into four main groups, which are Transportation, Operations, In Space Support and Surface Support, as shown in figure 3.

TRANSPORTATION
High performance human transfer
High Speed Earth Manned EDL
High Capacity Cargo Transfer
Orbit Cargo Insertion (non propulsive)
Destination Cargo Entry
Destination Manned Entry
Destination Cargo D&L
Destination Manned D&L
Destination Manned Ascent
Destination Cargo Ascent

OPERATIONS
Advanced RvD
Long Range Communications (high data rate)
Medium Range Communications
Short Range Communications
Reduced gravity drilling & samples mgmt.
Low-g bodies anchoring, drilling & samples management
Robotic tele-operations
Safe In-Space Elements Separation

SUPPORT – IN SPACE
In-Space Multiple dockings
In-Space Cryogenic Fuel Management
In Space Advanced Power
In-Space Advanced Thermal
In-Space High Capacity Storage
In-Space Advanced Life Support
In-Space Advanced Human Health Support
In-Space Advanced Human Habitability
In-Space Radiation Protection
In-Space Advanced Robotics
In-space advanced EVA

SUPPORT - SURFACE
Surface Multiple dockings
Surface Cryogenic Fuel Management
Surface Advanced Power
Surface Advanced Thermal
Surface Advanced Life Support
Surface Advanced Human Health Support
Surface Advanced Human Habitability
Surface Radiation Protection
Surface Advanced Robotics
Atmospheric ISRU
Soil ISRU
Surface Advanced EVA
Low-g bodies mobility
Surface Mobility

Fig. 3: Mars required capabilities.

The list of Mars required capabilities represents the starting point for the definition of the HSE scenario, which was built, as a matter of fact, on the basis of a "capabilities analysis", aimed at identifying the intermediate destinations missions which best allow a gradual achievement of those capabilities.

2.2. HSE Intermediate Destinations Concepts

To build up the scenario, once fixed the last mission (Mission to Mars NASA DRA 5.0), the intermediate destinations had to be selected.

Seven intermediate destinations were identified as possible targets in the path for exploration:

- Low Earth Orbit (LEO), considered mainly for the easy accessibility from Earth and for the presence of the already available International Space Station (ISS);
- Medium or High Earth Orbits (MEO/HEO), interesting because of their medium accessibility cost from Earth and for their more Deep Space-like environment;
- Cis-Lunar space (Earth-Moon Lagrangian Points), which is characterized by a deep space environment and allows an increased science return from the Moon;
- Moon, for which both Sortie Missions and surface Outpost possibilities were considered, in order to perform exploration on the lunar surface as well as to prepare for Mars exploration;
- Near Earth Asteroids (NEA), which give the possibility to perform a significant mission (closer than Mars), with analogous Mars mission deep-space aspects [19];
- Mars Moons, considered as a possibility for a Mars mission rehearsal, with reduced complexity and tele-operations of Mars assets;
- Mars Orbit, as Mars mission rehearsal, with reduced complexity.

For these seven destinations several Mission Concepts were defined, deriving from the combination of alternative "first-level key decisions", which are very high level concept attributes.

In particular tree diagrams were built, providing the alternative possible concepts for the various destinations. In figure 4 the case of the cis-lunar space is reported, as an example.

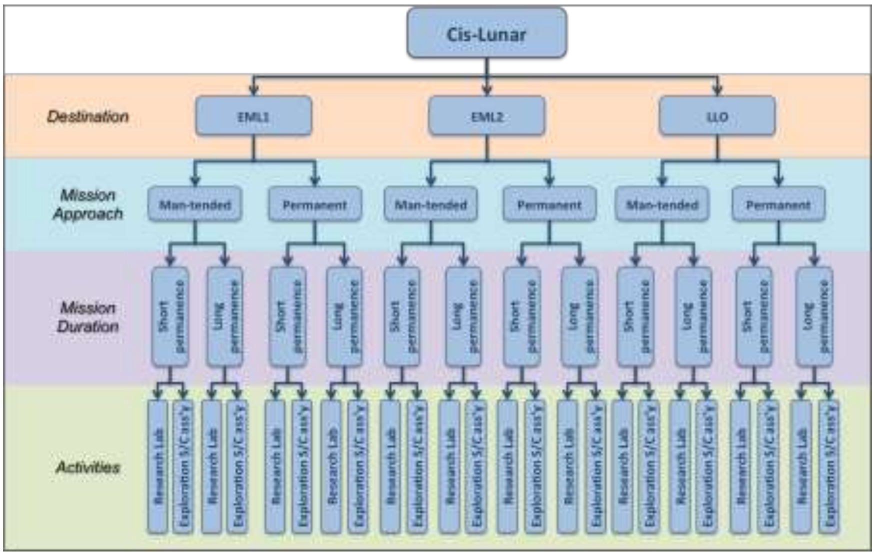

Fig. 4: Cis-Lunar Mission Concepts Tree Diagram

For this specific destination, the “first-level key decisions” are:

- destination, which can be the first or the second Earth Moon Lagrangian (EML) point, or a Low Lunar Orbit (LLO);
- mission approach, that is if the infrastructure is to be envisioned as a men-tended or a permanently inhabited station;
- mission duration, which refers to a short permanence (less than two weeks) versus a long permanence (more than two weeks up to several months) of the crew on the station;
- activities to be performed, which can be research and technological test, or also supporting the assembly of spacecraft for further exploration.

Each branch of the tree diagram represents a potential mission concept. In order to reduce the number of “candidate concepts”, among which only one has to be selected[3], for each “first-level key decision” the alternative options were qualitatively compared with each other, and only the most significant solutions were maintained as possible options (“candidate concepts”). Specifically, the major pros and cons of each option were identified and finally the most valuable for the overall scenario was selected.

For example, the Earth Moon Lagrangian point 1 was selected as destination mainly because of its higher accessibility from Earth and lower access cost, for the direct telecommunications visibility with ground segments and its good capability to support Moon surface activities, both robotic and human (assumed on the Moon near side).

As result of these evaluations, for the cis-lunar destination two concepts were maintained as “candidate concepts” (to be further considered in the following step of the process), which are:

- Cis-Lunar 1, envisaging an EML1 men-tended station, with the short permanence option and to be used mainly as research laboratory;
- Cis-Lunar 2, envisaging an EML1 men-tended infrastructure, with the long permanence option and capable to support the assembly of exploration S/C.

Analogously to what described for the Cis-Lunar case, similar considerations were done for the other six destinations, and finally 24 “candidate concepts” were identified. The main features of the 24 “Candidate Concepts” (at the level of the “first-level key decisions”) are provided in table II.

Destination	Candidate Concept	Main Features
LEO	ISS	• Permanent • Long Permanence • Research & techs test lab
	Equatorial Post-ISS	• Equatorial Post-ISS • Men-Tended • Long Permanence • Research Lab & Exploration S/C assembly

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[3] It is assumed that only one concept for each destination has to be included in the overall HSE Scenario (see section *“2.3. Capabilities Analysis”*)

MEO/HEO	HEO1	• HEO • Men-Tended • Short Permanence • Research & techs test lab
	HEO2	• HEO • Men-Tended • Long Permanence • Exploration S/C assembly
Cis-Lunar	CL1	• EML1 • Men-Tended • Short Permanence • Research laboratory
	CL2	• EML1 • Men-Tended • Long Permanence • Exploration S/C support
Moon Sorties	MS1	• Direct Approach • Long Stay • Long Exploration Range • Pre-Deployed Cargo
	MS2	• Direct Approach • Short Stay • Short Exploration Range • All up Cargo
	MS3	• Staging in cis-lunar • Long Stay • Long Exploration Range • Pre-Deployed Cargo
	MS4	• Staging in cis-lunar • Short Stay • Short Exploration Range • All up Cargo
Moon Outpost	MO1	• Direct Approach • Men-Tended • Long Stay • Long Exploration Range • Pre-Deployed Cargo
	MO2	• Direct Approach • Men-Tended • Short Stay • Long Exploration Range • Pre-Deployed Cargo
	MO3	• Staging in cis-lunar • Men-Tended • Long Stay • Long Exploration Range • Pre-Deployed Cargo
	MO4	• Staging in cis-lunar • Men-Tended • Short Stay • Long Exploration Range • Pre-Deployed Cargo
NEA	NEA1	• LEO Departure • Pre-Deployed Cargo • No-landing • Exploration Vehicle
	NEA2	• LEO Departure • All up Cargo • No-landing • Exploration Vehicle
	NEA3	• Cis-Lunar Departure • Pre-Deployed Cargo • No-landing • Exploration Vehicle
	NEA4	• Cis-lunar Departure • All up Cargo • No-landing • Exploration Vehicle
Mars Moons	DMS1	• Deimos • LEO departure • Pre-deployed Cargo
	DMS2	• Deimos

		• LEO departure • All up Cargo
	DMS3	• Deimos • Cis-lunar departure • Pre-deployed Cargo
	DMS4	• Deimos • Cis-lunar departure • All up Cargo
Mars Orbit	MOr1	• LEO departure • Pre-deployed station • Men-tended
	MOr2	• Cis-lunar departure • Pre-deployed station • Men-tended

Table II: Selected “Candidate Concepts”

2.3. Capabilities Analysis

For the 24 “candidate concepts” an analysis of capabilities, both required and applicable[4], was carried out in order to identify which of them are the most interesting to be included in the HSE scenario according to the philosophy behind the study (to maximize the capabilities achievement in view of the Mars mission).

The matrix shown in figure 5 represents the obtained capabilities map, for the 24 selected “candidate concepts”. The list on the left side of the matrix includes additional capabilities, with respect to those needed for Mars (see Figure 3), which were identified as necessary for the intermediate destinations, even if not required for the Mars mission.

As introduced before, the capabilities are expressed as high level functions, and in this regards no distinction is done in their definition to specify the destination which they refer to. However, the differences related to the various destinations environments are considered in the assessment of the requirements for the mission elements and to identify the “design improvements” needed when moving from one destination to the following ones (for additional details please see section *“2.4.4. HSE Scenario Elements Summary”*).

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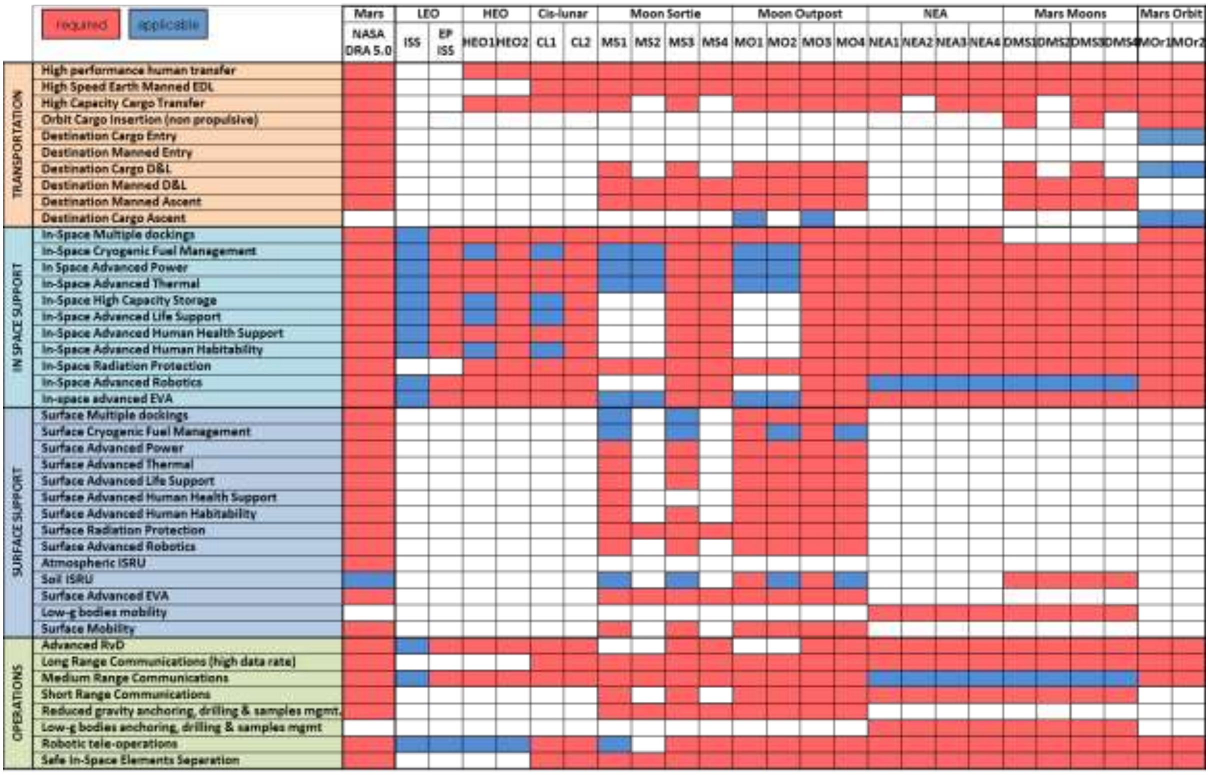
[4] “Required” means enabling or highly impacting on the overall mission/architecture, while “Applicable” is used if it is possible to be implemented and achieved, even if not strictly needed.



	🟥 required 🟦 applicable	Mars	LEO		HEO		Cis-lunar		Moon Sortie				Moon Outpost				NEA				Mars Moons				Mars Orbit	
		NASA DRA 5.0	ISS	EP ISS	HEO1	HEO2	CL1	CL2	MS1	MS2	MS3	MS4	MO1	MO2	MO3	MO4	NEA1	NEA2	NEA3	NEA4	DMS1	DMS2	DMS3	DMS4	MOr1	MOr2
TRANSPORTATION	High performance human transfer	🟥			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	High Speed Earth Manned EDL	🟥					🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	High Capacity Cargo Transfer	🟥			🟥	🟥	🟥	🟥	🟥		🟥		🟥	🟥	🟥	🟥	🟥		🟥	🟥	🟥		🟥	🟥	🟥	🟥
	Orbit Cargo Insertion (non propulsive)	🟥																			🟥		🟥		🟥	🟥
	Destination Cargo Entry	🟥																							🟦	🟦
	Destination Manned Entry	🟥																								
	Destination Cargo D&L	🟥							🟥		🟥		🟥	🟥	🟥	🟥					🟥		🟥		🟦	🟦
	Destination Manned D&L	🟥							🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥					🟥	🟥	🟥	🟥		
	Destination Manned Ascent	🟥							🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥					🟥	🟥	🟥	🟥		
	Destination Cargo Ascent												🟦		🟦										🟦	🟦
IN SPACE SUPPORT	In-Space Multiple dockings	🟥	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥					🟥	🟥
	In-Space Cryogenic Fuel Management	🟥	🟦	🟥	🟦	🟥	🟦	🟥	🟦	🟦	🟥	🟥	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	In Space Advanced Power	🟥	🟦	🟥	🟥	🟥	🟥	🟥	🟦	🟦	🟥	🟥	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	In-Space Advanced Thermal	🟥	🟦	🟥	🟥	🟥	🟥	🟥	🟦	🟦	🟥	🟥	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	In-Space High Capacity Storage	🟥	🟦	🟥	🟦	🟥	🟦	🟥			🟥	🟥			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	In-Space Advanced Life Support	🟥	🟦	🟥	🟦	🟥	🟦	🟥			🟥	🟥			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	In-Space Advanced Human Health Support	🟥	🟦	🟥	🟥	🟥	🟥	🟥			🟥	🟥			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	In-Space Advanced Human Habitability	🟥	🟦	🟥	🟦	🟥	🟦	🟥			🟥	🟥			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	In-Space Radiation Protection	🟥			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	In-Space Advanced Robotics	🟥	🟦	🟥	🟥	🟥	🟥	🟥			🟥	🟥			🟥	🟥	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟥	🟥
	In-space advanced EVA	🟥	🟦	🟥	🟥	🟥	🟥	🟥	🟦	🟦	🟥	🟥	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
SURFACE SUPPORT	Surface Multiple dockings	🟥							🟦		🟦		🟥	🟥	🟥	🟥										
	Surface Cryogenic Fuel Management	🟥							🟦		🟦		🟥	🟦	🟥	🟦										
	Surface Advanced Power	🟥							🟥		🟥		🟥	🟥	🟥	🟥										
	Surface Advanced Thermal	🟥							🟥		🟥		🟥	🟥	🟥	🟥										
	Surface Advanced Life Support	🟥							🟥		🟥		🟥	🟥	🟥	🟥										
	Surface Advanced Human Health Support	🟥							🟥				🟥	🟥	🟥	🟥										
	Surface Advanced Human Habitability	🟥							🟥		🟥		🟥	🟥	🟥	🟥										
	Surface Radiation Protection	🟥							🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥										
	Surface Advanced Robotics	🟥							🟥		🟥		🟥	🟥	🟥	🟥										
	Atmospheric ISRU	🟥																								
	Soil ISRU	🟦							🟦		🟦		🟥	🟦	🟥	🟦					🟥	🟥	🟥	🟥		
	Surface Advanced EVA	🟥							🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥										
	Low-g bodies mobility																🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		
	Surface Mobility	🟥							🟥		🟥		🟥	🟥	🟥	🟥										
OPERATIONS	Advanced RvD	🟥	🟦	🟥	🟥	🟥	🟥	🟥			🟥	🟥			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Long Range Communications (high data rate)	🟥					🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Medium Range Communications	🟥	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟥	🟥
	Short Range Communications	🟥							🟥		🟥		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		
	Reduced gravity anchoring, drilling & samples mgmt.	🟥							🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥										
	Low-g bodies anchoring, drilling & samples mgmt																🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		
	Robotic tele-operations	🟥	🟦	🟦	🟦	🟦	🟥	🟥	🟦		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Safe In-Space Elements Separation	🟥					🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

Fig. 5: Capabilities Map

This matrix provides a clear mapping of the capabilities through the various destinations and according to the concepts characteristics. The red cells indicate those capabilities are required, while the blue ones refer to the applicability of the specific capability at the different destinations. It is clear from the matrix that the ISS does not require any of the listed capabilities (that is logical being the ISS already complete and operative), but some of them can be applied there. This allows understanding that the first step shall be the exploitation as much as possible of the station to achieve those capabilities. Analogous observations can be done for the other concepts.

Starting from this wide picture of concepts, the following step in the "capabilities analysis" was to select the minimum number of destinations concepts that allows the demonstration and achievement of all the Mars Required Capabilities in intermediate locations (where they can be required or applicable).

To accomplish this task, the following driving criteria were followed:

- an incremental selection process was adopted, from closer and "easier" to further and "harder" destinations: starting from locations with less demanding requirements (e.g. cis-lunar) and gradually moving to more challenging targets (e.g. Moon, NEA, Mars, etc.), in terms of mission durations, needed resources and propellant, psychological aspects, possibility to "quickly" return to Earth;
- the possibility to reuse already existing space infrastructures was taken in account (e.g. ISS), in order to maximize their exploitation and reduce the overall costs (e.g. post-ISS was discarded in favour of ISS because it would imply much higher costs with almost the same demonstration opportunities);
- coupled concepts were preferred since they allow more flexibility, adaptability and reusability of elements: for example the Moon Sortie concept is envisaged to rely on the station deployed in cis-lunar, thus simplifying the architecture and concept of operations, since the cis-lunar station represents a staging post, which can have also a reusable lander to support multiple Moon surface missions or which can provide the astronauts with a shelter, in case of an emergency situation occurs during a Moon surface mission;
- no more than one concept for each destination was selected, in order to keep the overall scenario as "simple" as possible and therefore implicitly the cost of the overall scenario as low as possible.

According to these criteria, the various concepts were analysed and compared and finally five out of the 24 concepts were selected to be part of the overall HSE scenario. Specifically, the selected mission concepts are:

- ISS, that relies on an already existing infrastructure, for which all the in-space support capabilities (except for the Advanced Radiation Protection), and three Operations capabilities are applicable;
- CL2, coupled with Moon Sortie/Outpost and for which all the In-space Support capabilities are required (CL1 can be considered as a first operational phase of CL2);
- MS3, coupled with CL2 and for which three additional Transportation and two additional Operations capabilities are required (with respect to ISS and CL2), and almost all the Surface Support capabilities and all In-space Support capabilities are required or applicable.
- MO3, coupled with CL2 and for which all the In space Support capabilities, the Advanced RvD, Surface Advanced Human Health Support and Soil ISRU are required (not in MS3); Surface Support capabilities can be demonstrated at increased level with respect to MS3;
- NEA1, which generally allows the same capabilities as CL2 except for some dedicated required capabilities (not needed for Mars) and two additional Operations Capabilities [20, 21].

The MEO/HEO concepts were both discarded, since they do not provide significant demonstration possibilities, also considering the ISS and CL2 concepts. Similarly the Mars Moons and Mars Orbit concepts were discarded, since they do not provide any significant advancement in the Mars required capabilities achievement. It has to be underlined that the Mars orbit concept would foresee human mission to an infrastructure deployed in Mars orbit (human on-orbit activities), without landing on the Mars surface, and could be seen as a possibility to perform a Mars mission rehearsal, at least for what concerns the in-space phase, with reduced complexity, since no EDL systems would be necessary. According to this, few additional capabilities could be achieved; in particular, the cargo entry, descent, landing and ascent capabilities can be considered applicable, since the possibility to carry to Mars an unmanned system (like a dedicated payload for the mission) to deploy robotic assets on the surface is not excluded (maybe to perform tele-operation activities)[5]. However the complexity of such kind of concept (which includes manned missions to Mars orbit) would very high and may not be justified by so limited advancement in capabilities achievement. For this reason it was finally discarded, while a dedicated concept was introduced, which instead envisages heavy robotic missions and allows the implementation of additional capabilities not achievable in the other concepts. This sixth concept, called Mars Preparation (MP) concept (see figure 6), is characterized by some unmanned missions to Mars Orbit and Mars Surface, to demonstrate the missing capabilities (e.g. orbit cargo insertion, cargo entry, descent and landing and atmospheric ISRU), except for Destination Manned Entry, Descent, Landing and Ascent[6] that can be partially demonstrated through human rated missions and elements.

The MP concept is characterized by three phases, including several missions. The first phase includes a Mars sample return mission, the second phase includes a Mars habitability test mission and the last phase comprises a Mars unmanned rehearsal mission and a mission for pre-deploying a Mars Relay Satellite. This concept envisages the implementation of several elements, which actually represent the precursors of the human mission ones, as for example the aeroshell, to be implemented also during the astronauts' entry phase, a demo of the Mars Ascent Vehicle.

The functions listed in the capabilities map (figure 5) are related to phases characterized by different levels of risks. Within the study no detailed risks analyses were performed; however, specific considerations were done especially for the most critical functions and the associated mission elements. The approach that was followed took into account that some phases are particularly risky and therefore attention was paid to how implementing the most critical mission elements through the various destinations. In this regard, for example, considering the Mars EDL that is very critical, several aeroshell elements are included in the MP concept, which gradually improve their features till achieving the characteristics required for the human mission. Another example is represented by the nuclear propulsion, which is considered very challenging and for which a demo is envisaged prior to actually implement it. Moreover, the first missions relying on nuclear propulsion are unmanned missions, which are less critical than manned ones (see sections *"2.4.1. Example Case: Cis-Lunar"* and *"2.4.4. HSE Scenario Elements Summary"*).

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[5] The surface support capabilities are not considered required/applicable, since this concept is intended as a simpler concept limited to the human on-orbit activities. Of course, specific payloads could be included, as for example ISRU demo: these aspects were specifically addressed considering an additional robotic concept.

[6] These refer to systems with astronauts on-board and the attribute "manned" is generally used to distinguish from the cargo (just a matter of nomenclature); however, the systems used in the unmanned missions will be conceived so that they allow implementing the same technologies, considering the same constraints, in order to validate them.

		Mars						
		NASA DRA 5.0	ISS	CL2	MS3	MO3	NEA1	MP
TRANSPORTATION	High performance human transfer	🟥		🟥	🟥	🟥	🟥	
	High Speed Earth Manned EDL	🟥		🟥	🟥	🟥	🟥	
	High Capacity Cargo Transfer	🟥		🟥	🟥	🟥	🟥	🟥
	Orbit Cargo Insertion (non propulsive)	🟥						🟥
	Destination Cargo Entry	🟥						🟥
	Destination Manned Entry	🟥						
	Destination Cargo D&L	🟥			🟥	🟥		🟥
	Destination Manned D&L	🟥			🟥	🟥		
	Destination Manned Ascent	🟥			🟥	🟥		
	Destination Cargo Ascent					🟦		🟥
IN SPACE SUPPORT	In-Space Multiple dockings	🟥	🟦	🟥	🟥	🟥	🟥	
	In-Space Cryogenic Fuel Management	🟥	🟦	🟥	🟥	🟥	🟥	🟥
	In Space Advanced Power	🟥	🟦	🟥	🟥	🟥	🟥	
	In-Space Advanced Thermal	🟥	🟦	🟥	🟥	🟥	🟥	
	In-Space High Capacity Storage	🟥	🟦	🟥	🟥	🟥	🟥	
	In-Space Advanced Life Support	🟥	🟦	🟥	🟥	🟥	🟥	
	In-Space Advanced Human Health Support	🟥	🟦	🟥	🟥	🟥	🟥	
	In-Space Advanced Human Habitability	🟥	🟦	🟥	🟥	🟥	🟥	
	In-Space Radiation Protection	🟥		🟥	🟥	🟥	🟥	
	In-Space Advanced Robotics	🟥	🟦	🟥	🟥	🟥	🟦	🟥
	In-space advanced EVA	🟥	🟦	🟥	🟥	🟥	🟥	
SURFACE SUPPORT	Surface Multiple dockings	🟥			🟦	🟥		
	Surface Cryogenic Fuel Management	🟥			🟦	🟥		🟥
	Surface Advanced Power	🟥			🟥	🟥		🟥
	Surface Advanced Thermal	🟥			🟥	🟥		🟥
	Surface Advanced Life Support	🟥			🟥	🟥		
	Surface Advanced Human Health Support	🟥				🟥		
	Surface Advanced Human Habitability	🟥			🟥	🟥		
	Surface Radiation Protection	🟥			🟥	🟥		🟥
	Surface Advanced Robotics	🟥			🟥	🟥		🟥
	Atmospheric ISRU	🟥						🟥
	Soil ISRU	🟦			🟦	🟥		🟦
	Surface Advanced EVA	🟥			🟥	🟥		
	Low-g bodies mobility						🟥	
	Surface Mobility	🟥			🟥	🟥		🟥
OPERATIONS	Advanced RvD	🟥	🟦	🟥	🟥	🟥	🟥	🟥
	Long Range Communications (high data rate)	🟥		🟥	🟥	🟥	🟥	🟥
	Medium Range Communications	🟥	🟦	🟥	🟥	🟥	🟦	🟥
	Short Range Communications	🟥			🟥	🟥	🟥	🟥
	Reduced gravity anchoring, drilling & samples mgmt.	🟥			🟥	🟥		
	Low-g bodies anchoring, drilling & samples mgmt						🟥	
	Robotic tele-operations	🟥	🟦	🟥	🟥	🟥	🟥	
	Safe In-Space Elements Separation	🟥		🟥	🟥	🟥	🟥	🟥

Fig. 6: Capabilities Map – Selected Concepts Summary

Summarizing, six intermediate destinations concepts are included in the reference scenario. It is worth to underline that the NEA mission does not offer a significant added value being almost equivalent to the cis-lunar concept in terms of Mars required capabilities achievement. This is already an important result, which can drive strategic decisions for the future solar system exploration. In the HSE reference scenario, the NEA mission concept has been however included, since it really gives the chance to perform a Mars rehearsal mission, at least for the travel phase (deep-space flight), with a reduced complexity with respect to the Mars mission. Moreover, the analysis here described only focuses on the technological aspects, but actually a human mission to a NEA would also have a high scientific interest and would offer the possibility to test systems for the deflection of potentially hazardous asteroids.

2.4. HSE Scenario Definition

To build up the HSE Scenario, starting from the six mission concepts discussed in the previous section, all the missions and the relative architectures were defined.

All the evaluations carried out to assess the missions, relied on some preliminary assumptions, hereafter reported:

- the assessment of all the destinations concepts was done always considering the NASA DRA 5.0 study as the main reference at all the levels, within the idea of an incremental path of Mars required capabilities demonstration;
- mission objectives different from the technological test for the Mars mission (e.g. scientific, research, space promotion) were only partially considered;
- the number of missions proposed for each destination concept is a minimum estimate; in case of failures the number of missions can increase, suggesting for repetitions (Apollo Program-like approach);
- mission aborts options were not considered in the human missions of any destination concept;
- no considerations on costs and risks were performed;
- dedicated calculations were performed for the evaluation of the transportation elements or stages;

- no models were used for the assessment of the logistics missions, in terms of their numbers and upload capability; the reference values are first approximations based on past and current similar missions (e.g. ATV to the ISS);
- the Ground and the Launch segments were not considered in the missions' definition.

State-of-the-art and future planned launchers were considered and in particular the launchers listed in table III were assumed for the present study.

Name	**Availability**	**LEO P/L mass [t]**	**Launch Site**	**Notes**
Ariane 5 ES (A5_ES)	available	>20	Guiana Space Centre	Unmanned
Ariane 5 ME (A5_ME)	2016	11.2 to GTO	Guiana Space Centre	Unmanned
Falcon 9 Heavy (F9H)	2013 - 2014	53 (200km, 28.5°)	Cape Canaveral	Unmanned
Space Launch System (SLS_70)	2017	70	Kennedy Space Centre	Unmanned
Space Launch System (SLS_100)	?	100	Kennedy Space Centre	Unmanned
Space Launch System (SLS_130)	?	130	Kennedy Space Centre	Unmanned
Crew-rated Atlas V (At5_M)	2016-2017	28	Cape Canaveral	Manned
Space Launch System (SLS_70M)	2017	70	Kennedy Space Centre	Manned

Table III: Assumed Launchers

For each mission concept the analysis went through several steps, as schematically illustrated in figure 7. The various steps are only briefly described here, but a specific example case (cis-lunar concept) is reported in the following section.

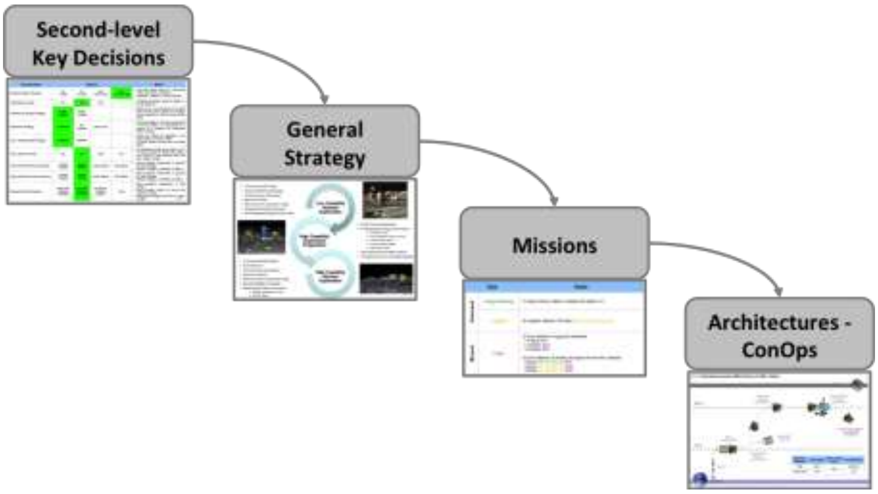


Fig. 7: Mission Concept Analysis Work Flow

First of all, several options for major architecture-level attributes ("Second-level Key Decisions") were qualitatively evaluated in order to select the most significant ones.

The second step was the definition of the "General Strategy" to be adopted: the main phases were identified and described.

After having defined the general strategy, the type (e.g. manned or robotic) and the minimum total number of missions were determined.

At this point, all the architectures corresponding to the identified missions were built, and an assessment of the needed launchers and space elements was performed.

Obviously, the process just described was applied to all the six mission concepts composing the overall scenario. In the following, only an example is discussed, that is the cis-lunar case.

2.4.1. Example Case: Cis-Lunar

The process of analysis of the cis-lunar case for the definition of the missions and the architectures started from the identification and evaluation (qualitative) of specific "Second-level key decisions". These refer to major architecture-level attributes of the concept, for which different options were identified and compared.

For each key decision a specific option was then selected, according to the philosophy behind the study, taking in mind the final objective of the human mission to Mars (NASA DRA 5.0).

The key decisions for the cis-lunar destination are summarized in table IV, in which the alternative options are shown, as well as the justification of the final choice.

Key decision	Options				Notes
Number of human Missions	3	**6**	>6		Six manned missions are considered: the first three (increasing durations) for research and technologies tests, the other three (6 months) in support of the Moon missions
Crew Members	2	3	**4**	>4	Crew size of 4 is considered, since it is representative of a Moon mission.
Cargo In-Space Propulsion	Cryogenic Propulsion System (CPS)	Nuclear Thermal Rocket (NTR)	Solar Electric Propulsion (SEP)		CPS is chosen because it is considered too challenging to have NTR (high capacity required) available for 2017, when the station is envisioned to be deployed.
Crew In-Space Propulsion	Cryogenic Propulsion System (CPS)	Nuclear Thermal Rocket (NTR)			CPS is initially adopted, while NTR is implemented in the later missions (after having been tested and implemented in the logistics missions)
Logistics In-space Propulsion	Nuclear Thermal Rocket (NTR)	Cryogenic Propulsion System (CPS)			NTR is adopted for the logistics missions which represent the first possibility to implement and get that capability (low capacity NTR)

Table IV: Second-level key decisions

In summary, six manned missions with a crew of four astronauts were considered. For what concerns the in-space propulsion, cryogenic propulsion is to be adopted for the station delivery to EML1 and for the first manned missions. Nuclear propulsion is instead adopted for all the logistics missions and for the last crew missions.

The following step was the assessment of the mission strategy. In particular for the cis-lunar case the mission strategy foresees three main phases.

The first phase starts with the deployment of the station (EML1-HAB) in EML1 [22, 23, 24], relying on cryogenic propulsion. During this phase of autonomous operations (before the first crew visit), the station is used for research (scientific experiments operated from ground) and test of technologies.

The station deployed in cis-lunar is intended as a men-tended infrastructure, and periodic crew visits are envisioned. In particular, the first three manned missions are of increasing duration (15 days, 3 and 6 months respectively). In this second phase, besides scientific research and technologies tests activities, tele-operation activities of robotics assets on the Moon surface are to be considered.

The last phase is in support of the Moon missions and, specifically, three manned missions are envisaged, in particular to perform tele-operation activities of robotic assets on the Moon surface and provide support for the Moon base deployment and activation, as well as support to crew operating on the Moon surface.

At this point, a more detailed characterization of the different missions was performed.

A minimum number of 13 missions was derived as needed. In particular they can be divided into three different mission types:

- Unmanned Cargo Delivery Mission, which refers to the unmanned mission for the delivery of the cis-lunar station to EML1;
- Unmanned Logistics Missions, needed for the resupply of the station (six missions are assumed in correspondence of the crew missions);
- Crew Missions, which represent the crew visits at the station (six total missions).

For the three types of mission just mentioned, four different mission architectures were identified.

The first architecture refers to the cargo delivery mission. The sequence of operations is schematically shown in figure 8. The transfer stage utilizes cryogenic propulsion, to insert the station in the transfer trajectory towards EML1, while a service module attached to the EML1-HAB is in charge of Halo orbit insertion and station keeping.

In the pictures illustrating the mission architectures, the masses of the various elements are indicated, as well as the ΔV provided by the propulsive stages. Specifically, the value adopted for the EML1-HAB mass comes from previous studies used as reference [22, 23]

The propellants mass were evaluated using the classical rocket equation [25]:

$$M_{prop} = M_{fin}\left[\exp\left(\frac{\Delta V}{I_{sp} g_0}\right) - 1\right]$$

where for the HAB-SM and the CPS the dry mass was assumed equal to 5 and 7 t respectively, and the I_{sp} was assumed 326 and 465 sec respectively.

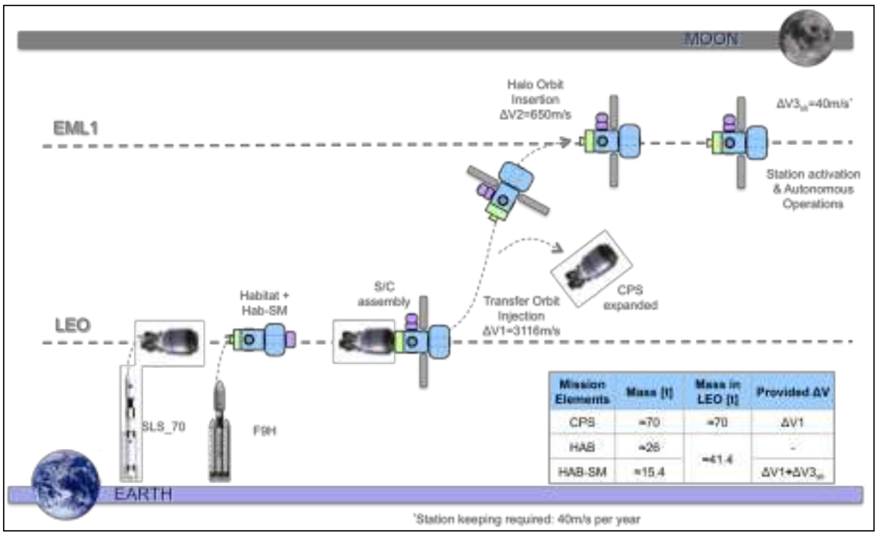


Fig. 8: Cis-Lunar Architecture – Cargo Delivery (EML1-HAB)

For what concerns the crew missions, two architectures were derived, as shown in figures 9 and 10, implementing cryogenic and nuclear propulsion, respectively.

Even in this case, the classical rocket equation was adopted for the evaluation of the initial mass in LEO. The computations were done assuming

- CEV mass equal to 9 t,
- CPS dry mass equal to 7 t,
- NTR dry mass equal to 10 t and I_{sp} = 900 sec.

The first two human missions are assumed to implement cryogenic propulsion, since it appears quite unlikely to have nuclear thermal rockets available for manned missions in 2018. Moreover it is assumed that before implementing nuclear propulsion in crewed missions, some experience shall be gained in unmanned missions (e.g. logistics missions).

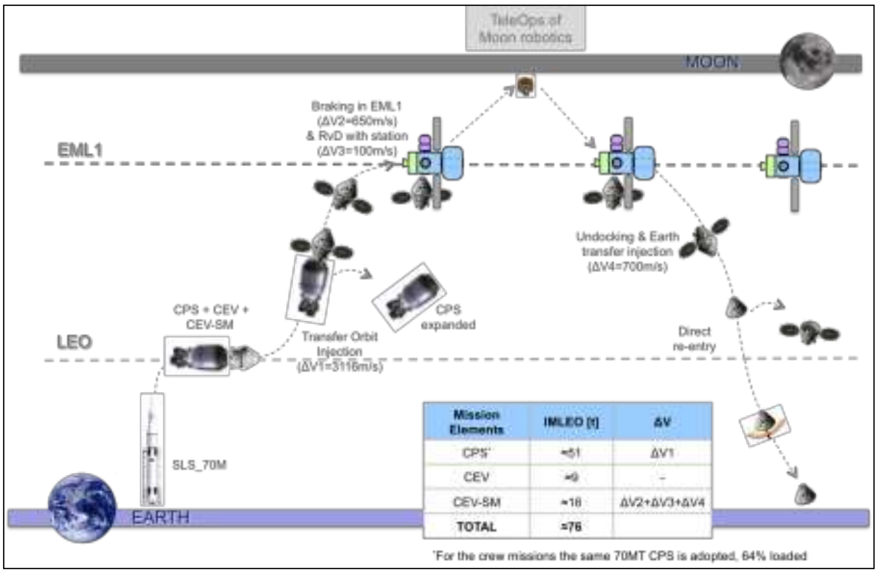
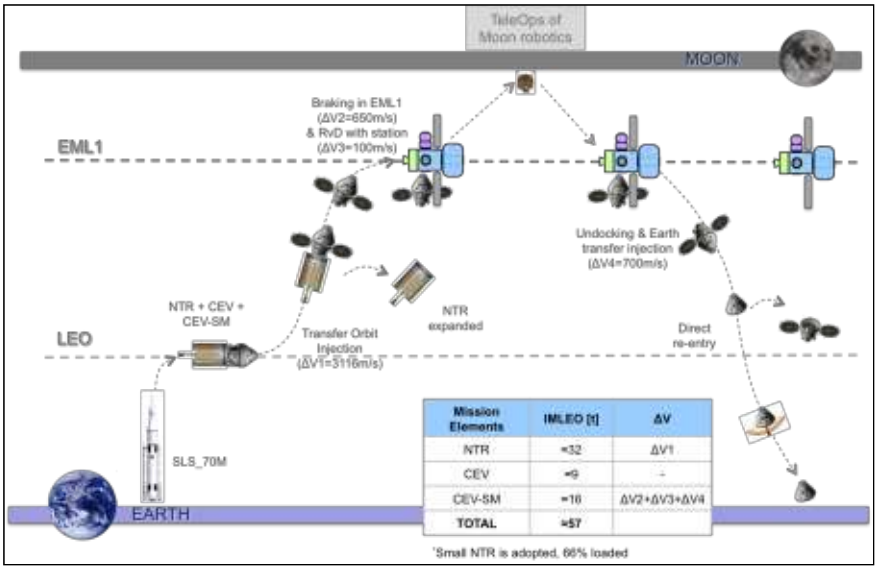


Fig. 9: Cis-Lunar Architecture – Crew Mission with Cryogenic Propulsion

The following missions (starting from 2020) instead implement nuclear propulsion, after having been tested and implemented in the unmanned logistics missions.



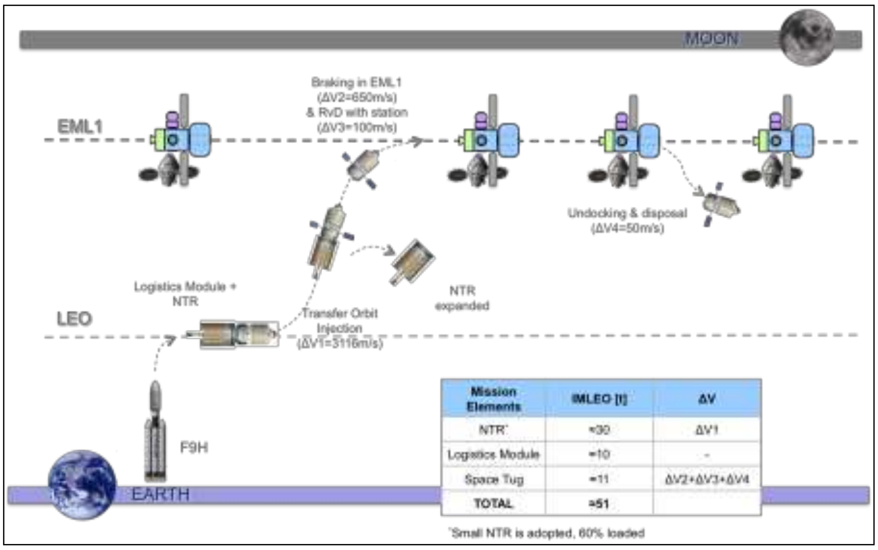
Mission Elements	IMLEO [t]	ΔV
NTR	≈32	ΔV1
CEV	≈9	-
CEV-SM	≈16	ΔV2+ΔV3+ΔV4
TOTAL	≈57	

*Small NTR is adopted, 66% loaded

Fig. 10: Cis-Lunar Architecture – Crew Mission with Nuclear Propulsion

The crew missions rely on the use of a Crew Exploration Vehicle (CEV) – like system with its service module [11].

The last identified architecture is shown in figure 11 that reports the sequence of operations of the logistics missions. The logistics delivery module is assumed to be an ATV-like system. This architecture envisages the use of a Nuclear Thermal Rocket (NTR) since the first mission, in order to validate this technology.



Mission Elements	IMLEO [t]	ΔV
NTR*	≈30	ΔV1
Logistics Module	≈10	-
Space Tug	≈11	ΔV2+ΔV3+ΔV4
TOTAL	≈51	

*Small NTR is adopted, 60% loaded

Fig. 11: Cis-Lunar Architecture – Logistics Mission.

According to the mission architectures just described ten different elements are needed to accomplish the CL2 concept missions, which are:

- Transportation Elements
  - Habitat-Service Module (1 unit)

    - CEV-Service Module (6 units)
    - CEV (6 units)
    - CPS (3 units)
    - Small NTR (10 units)
    - Space Tug (6 units)
- In Space Elements
    - Cis-lunar Habitat (1 unit)
    - Airlock (1 unit)
    - Logistics Module (6 units)
    - Robotic Arm (1 unit)

All these elements can be further classified as "New Project", "Upgraded Versions" and "Already Used" elements, with respect to previous steps of exploration (in this case the ISS concept). This allows easily visualizing and validating the approach adopted in the definition of the missions and of the whole scenario (additional details are provided in the section *"2.4.4. HSE Scenario Elements Summary"*).

2.4.2. HSE Scenario

The process just described for the Cis-Lunar concept, was followed for all the 6 mission concepts. At the end, a large number of missions were included in the HSE reference scenario and all the relative mission architectures were investigated, ending up with the overall set of elements needed to accomplish all the missions of the entire scenario. For all the details about the other destinations please refer to.

Summarizing all the results obtained for the various destinations the reference HSE scenario was built. It is shown in figure 12, where all the missions are indicated along the temporal reference window, going from 2014 to 2039, when the human mission to Mars is foreseen (the "star" in the top right corner of the graph refers to the NASA DRA 5.0 human expedition to Mars).

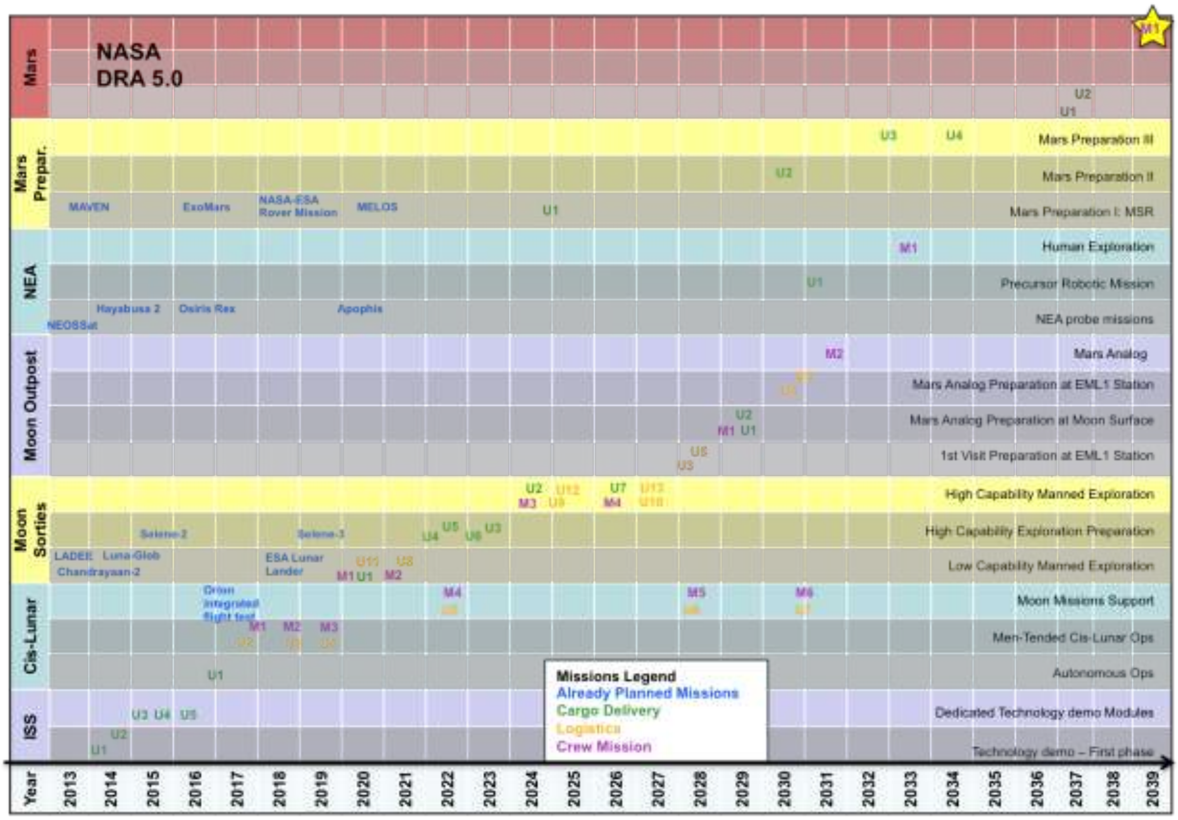


Fig. 12: Human Space Exploration Reference Scenario

The graph has to be read from the bottom to the top as the sequence of destinations is represented. For each destination the various phases of exploration are highlighted, using different colour tones for the rows in which each destination area is divided.

All the missions are indicated with a specific abbreviation and colour, to precisely identify them. In particular, the missions labelled with a *green U* are the unmanned missions for the delivery of the cargo, those labelled with a *pink M* are the crew exploration missions and those labelled with a *yellow U* are the unmanned logistics missions. Finally, already planned robotic missions are also included in the scenario (in blue).

2.4.3. HSE Scenario Launchers Summary

Table shown in figure 13 summarizes the needed launchers for all the scenario missions. The number of needed launchers for each mission derived from the mass evaluations carried out analogously to what previously described for the cis-lunar case. For each launcher the number of units needed for each destination is reported, specifying also the date when it is first needed at that destination. The total number of units as well as the planned availability date of the launchers is also highlighted.

Launcher		Number							Tot	Required Date							Min	Plan
		ISS	EML1	MS	MO	NEA	MP	Mars		ISS	EML1	MS	MO	NEA	MP	Mars		
Unmanned	**A5_ES**	5							**5**	2014							**2014**	Available
	A5_ME			1					**1**			2022					**2022**	2016
	F9H		7	8	2		5		**22**		2017	2020	2028		2030		**2017**	2013-2014
	SLS_70		1	7	6	1		1	**16**		2017	2020	2028	2031		2039	**2017**	2017
	SLS_100				2	1	2	5	**10**				2029	2033	2030	2037	**2029**	?
	SLS_130					1	1	3	**5**					2033	2032	2037	**2032**	?
Total Unmanned Launches									**59**									
Manned	**SLS_70M**		6	4	2				**12**		2018	2020	2029				**2018**	2017
	At5_M					1		1	**2**					2033		2039	**2033**	?
Total Manned Launches									**14**									

Fig. 13: HSE Scenario Launchers Summary

2.4.4. HSE Scenario Elements Summary

As explained before, for each one of the missions included in the scenario, the relative architecture and concept of operations were analysed, analogously to what described for the cis-lunar case. Furthermore, an assessment of the needed elements[7] derived from the architectures analysis. In the present paper, it is not possible to go into the details of each case. However, an overview of the obtained results is shown in figure 14, which reports a pictorial summary of all the elements needed through all the intermediate destinations.

The number reported next to every element image refers to the number of units needed at the specific destination. Moreover, a different colour is used to indicate that the element is a "New Project", an "Upgraded Version" or an "Already Used" element with respect to the previous step (red, yellow or green colour, respectively).

It is worth underlining that the graph shall be read starting from the bottom, representing the first intermediate destination, i.e. ISS, up to the top, representing the last step, i.e. Mars Preparation. The considerations about the elements came from the idea to have as much as possible a gradual "improvement" through the following destinations. This can be easily seen from the picture.

For example, if consider the Nuclear Thermal Rocket element, the first element appearing in the scenario is represented by a Demo at ISS. Then, there is a Small NTR ("Upgraded Version" with respect to the previous step) implemented in the cis-lunar concept and later on the same small NTR is used in the Moon missions ("Already Used") and so on.

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[7] The timeframes in which all the elements are needed derived from all the considerations done for the missions composing the scenario and shall be read as "desired dates". These times represent an indication of when the elements and technologies will be needed to accomplish specific missions, and in this respect could represent an input to define an adequate development plan.

Fig. 14: HSE Scenario Elements Summary

A clearer summary of the minimum number of different elements needed for all the destinations concepts is reported in figure 15, which also shows their changing *Design Status* with respect to the previous concepts. In particular the green colour is used to indicate elements already designed and implemented in previous destinations missions, the yellow colour indicates upgraded versions of the elements and the red colour is used to indicate totally new elements, not needed in previous destinations. The graph does not include the recurrent units but only the number of elements.

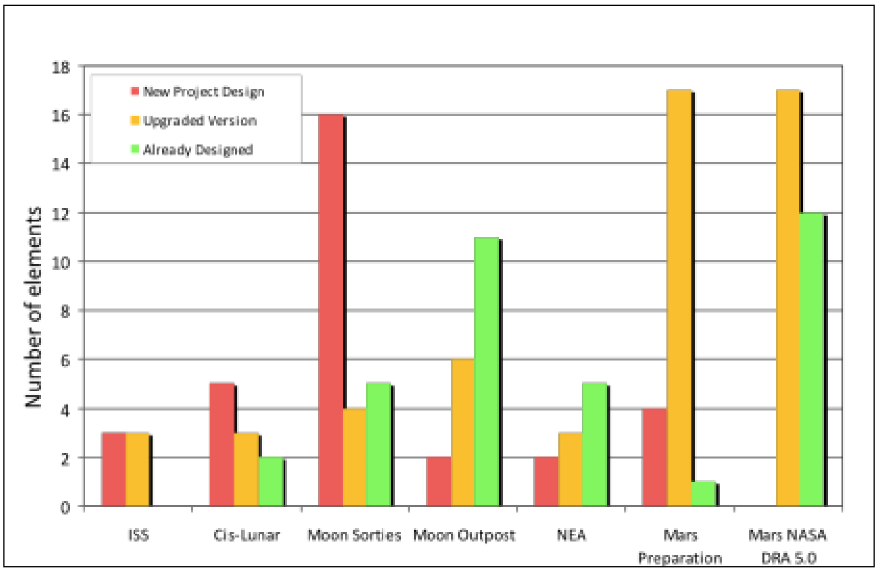


Fig. 15: HSE Scenario Elements Design Status

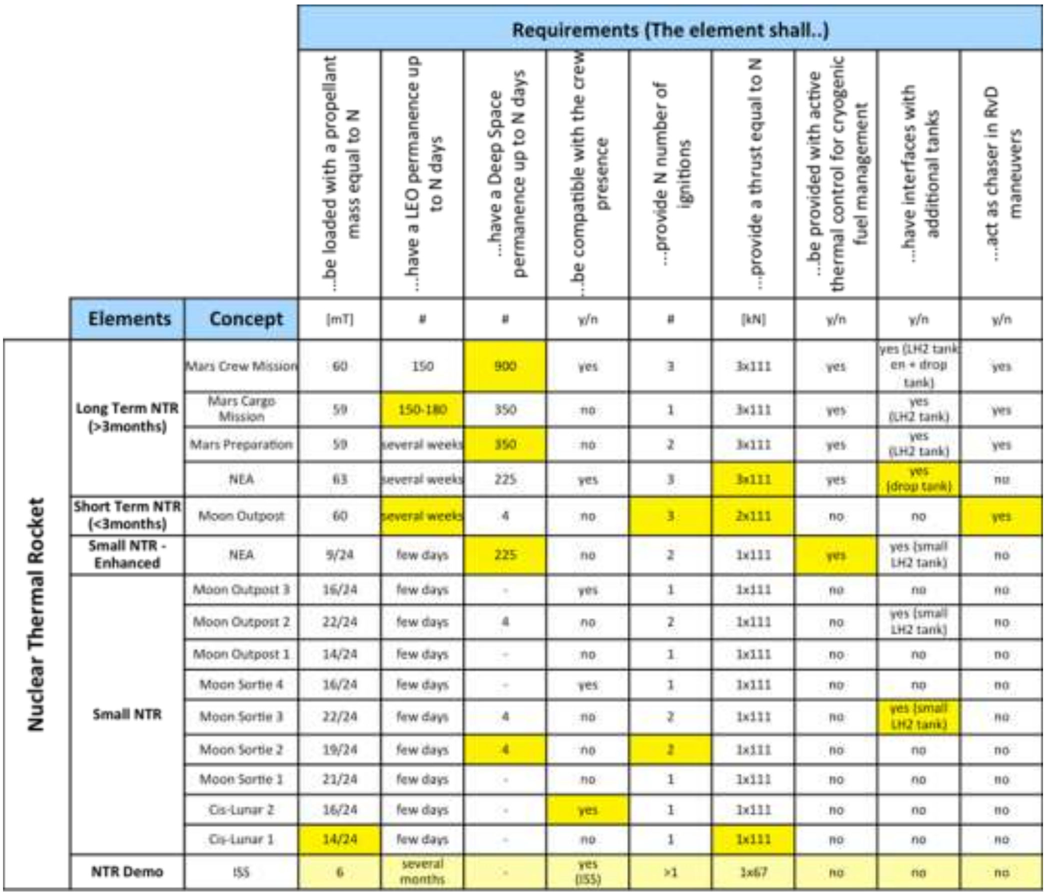
It appears clear from the graph that in the beginning a large number of new elements is needed, but going on through the following destinations the number of already available elements increases while the number of new designs decreases. The ISS concept elements are the additional modules needed for the test of some technologies. Specifically, the new projects refer to demo modules, i.e. NTR demo, inflatable demo and cryogenic fuel tank, while the upgraded versions refer to the ATV-like or PMM-like modules envisaged to carry to the ISS several technologies to be tested. Finally, for the Mars human mission, no new project designs are needed. This is perfectly in line with the philosophy adopted for the definition of the scenario and the assessment of the intermediate destinations missions, to gradually achieve the capabilities required to accomplish the reference human mission to Mars. It is worth noticing that some capabilities are implementable only during the human mission to Mars (as previously assessed in section *"2.3. Capabilities Analysis"*) but the corresponding elements used in this mission are in any case an "upgraded" version of previously adopted ones.

In order to provide a clearer understanding of how the upgrades in the design of the various elements have to be implemented through successive destinations, hereafter some details of a "commonalities analysis" are reported. This analysis aimed at identifying and verifying the commonalities among elements and at highlighting the major improvements that need to be introduced through various incremental destinations. It was performed per class of elements, in which all the elements were grouped [8]. Each class of elements includes similar elements satisfying more and more demanding requirements, corresponding to gradually improving design and development efforts. Hereafter, as an example, the nuclear thermal rocket class is discussed.

The Nuclear Thermal Rocket class of elements includes five elements:

- **NTR Demo**, which is the first element to be developed and deployed at the ISS to test this technology;
- **Small NTR**, to be used for the cis-lunar, Moon sortie and some of the Moon Outpost missions, with a maximum propellant capability of 24 t;
- **Small NTR-enhanced**, to be used during a longer mission (NEA mission) and therefore requiring a specific thermal control for propellant management;
- **Short Term NTR**, which has larger fuel loading capability and is used for mission duration shorter than three months;
- **Long Term NTR**, to be used for longer duration mission (more than three months).

Figure 16 reports an overview of the requirements for the elements belonging to the Nuclear Thermal Rocket class, highlighting the major requirement changes (yellow cells) passing from a previous element to the following one (the table shall be read starting from the bottom, i.e. closer destination, up to the top, i.e. furthest destination). Moreover the improvements needed for the same element for implementation in successive destinations missions are highlighted.



			Requirements (The element shall..)								
			…be loaded with a propellant mass equal to N	…have a LEO permanence up to N days	…have a Deep Space permanence up to N days	…be compatible with the crew presence	…provide N number of ignitions	…provide a thrust equal to N	…be provided with active thermal control for cryogenic fuel management	…have interfaces with additional tanks	…act as chaser in RvD maneuvers
	Elements	Concept	[mT]	#	#	y/n	#	[kN]	y/n	y/n	y/n
Nuclear Thermal Rocket	Long Term NTR (>3months)	Mars Crew Mission	60	150	900	yes	3	3x111	yes	yes (LH2 tank en + drop tank)	yes
		Mars Cargo Mission	59	150-180	350	no	1	3x111	yes	yes (LH2 tank)	yes
		Mars Preparation	59	several weeks	350	no	2	3x111	yes	yes (LH2 tank)	yes
		NEA	63	several weeks	225	yes	3	3x111	yes	yes (drop tank)	no
	Short Term NTR (<3months)	Moon Outpost	60	several weeks	4	no	3	2x111	no	no	yes
	Small NTR - Enhanced	NEA	9/24	few days	225	no	2	1x111	yes	yes (small LH2 tank)	no
	Small NTR	Moon Outpost 3	16/24	few days	-	yes	1	1x111	no	no	no
		Moon Outpost 2	22/24	few days	4	no	2	1x111	no	yes (small LH2 tank)	no
		Moon Outpost 1	14/24	few days	-	no	1	1x111	no	no	no
		Moon Sortie 4	16/24	few days	-	yes	1	1x111	no	no	no
		Moon Sortie 3	22/24	few days	4	no	2	1x111	no	yes (small LH2 tank)	no
		Moon Sortie 2	19/24	few days	4	no	2	1x111	no	no	no
		Moon Sortie 1	21/24	few days	-	no	1	1x111	no	no	no
		Cis-Lunar 2	16/24	few days	-	yes	1	1x111	no	no	no
		Cis-Lunar 1	14/24	few days	-	no	1	1x111	no	no	no
	NTR Demo	ISS	6	several months	-	yes (ISS)	>1	1x67	no	no	no

Fig. 16: NTR Commonalities Analysis

Analogous considerations were done for all the elements of the reference scenario, in order to verify how the design of the elements evolves through the various missions and to guarantee a step-by-step increase in the design and development efforts. These considerations would be very useful to support the plan of the agencies in the development of specific technologies and elements, taking specifically into account affordability issues.

3. Conclusions

The paper has presented the results obtained in the frame of the MITOR 2012 project, which was developed as collaboration between Politecnico di Torino and Massachusetts Institute of Technology (MIT).

It mainly focused on the description of the process that was followed and the methodologies adopted to define and analyse a reference scenario for the future Human Space Exploration.

The starting point for the present study was the reference human mission to Mars as defined by the NASA DRA 5.0. All the evaluations and major decisions were driven by the final objective to have a human expedition to the Red Planet by the end of 2030s.

Within the paper the adopted methodologies as well as the obtained results have been discussed.

In order to progressively achieve the required capabilities through incremental steps to finally accomplish the human mission to Mars, a minimum of six intermediate destinations concepts were evaluated necessary to be included in the future HSE reference scenario (2014-2037). Each concept, as it is defined, allows the demonstration of capabilities through correlated strategies, and common and evolutionary missions, architectures and elements. On the basis of design status analysis, it was verified that the scenario, as conceived, guarantees to achieve the capabilities required for the Mars expedition.

The results obtained with the described methodology can be a good starting point to take strategic decisions about future missions, eventually considering additional objectives. For example, the NEA mission concept does not represent a very high added value in the path of exploration if only the technological point of view is considered, even if it is very interesting to be considered as a rehearsal for the Mars mission, and moreover from the scientific and planetary defence standpoints.

The here presented methodology was based on a pure technical approach, which did not take into account cost considerations. Accordingly, the architectures for the various missions were defined on the basis of qualitative assessment of different parameters and in such a way to guarantee a progressive achievement of technological capabilities.

The process followed in the MITOR study has some similar aspects with other techniques being studied by other research groups. In particular, the MIT Space Architecture Group is working on an approach to select the most interesting architecture for any given destination [10], based on the identification of a comprehensive set of possible mission design alternatives and their evaluations via assessment of cost proxy metrics. Even in this study no direct calculations are done to estimate the cost, but the ranking of the architecture alternatives is performed on the basis of cost proxy metrics including the main drivers of cost, such as IMLEO and the number of development projects. Moreover, other parameters are taken into account and for them alternative options are considered and evaluated (e.g. number of crew, mission duration, etc.).

It is clear that the MITOR 2012 project methodology described in this paper has some similarities with the MIT Space System Architecture Group work, especially for what concerns the parameters considered for the architecture assessment, as for instance the number of crew members and the mission duration.

In addition, some quantitative assessments are part of the MITOR Project 2012 methodology for the definition of the architectures, mainly based on the estimation of the IMLEO.

However, at the higher scenario level, choices cannot be made basing on quantitative evaluations, but strategic decisions are to be taken to define the overall path for exploration before entering in the details of each step and deeper investigating every single mission.

On the other hand, some differences hold, mainly due to the fact that in the MITOR project the architecture selection was mainly driven by the final objective to get the capabilities required for the human mission to Mars, which not always allows for the most "cost-effective" solution. For example, if we limited to cis-lunar missions, the choice of nuclear propulsion would not be completely justified, and maybe conventional propulsion would be adopted. However, in view of the final mission to Mars, which relies on nuclear propulsion, it was decided to implement this technology even in closer destinations, in order to achieve the Mars required capability in a gradual way. This decision is therefore driven by the higher level scenario definition philosophy.

Furthermore, the MIT work limits its evaluation to a single destination at a time focusing on two primary functions (Habitation and Transportation) which are then further decomposed, while for the MITOR project the main objective was to build an overall scenario for exploration, considering multiple destinations and several elements classes in order to take into account the evolutions needed through the various steps.

According to what just discussed, it is possible to conclude that the MITOR Project 2012 has a good potentiality to assess which are the next destinations for the exploration of the space beyond LEO and to preliminary define the missions' architecture, identifying the most significant needed elements and technologies. The database produced as result of this analysis can be a valuable support in strategic decisions to define the future steps in the exploration of the solar system.

In particular in this paper, the focus was on a reference scenario built considering as the final target a human expedition to Mars in 2039; however the methodology will still be valid if a different final target or a different Mars mission opportunity is considered.

Future works can include an analysis of the costs associated to the generated scenario and to the related missions. However, even if preliminary cost evaluations are possible and could as a matter of fact be considered as an additional criteria to select the most suitable sequence of destination for future space exploration, the strategic decisions for space exploration roadmaps are certainly based on technical and cost considerations but are strongly affected by political and global worldwide economic issues, which are not likely to be predicted. Therefore, the results presented in this paper should be seen as a pure technical reference, which can drive opportunely the decisions of the agencies to place investments for the development of specific technologies and get ready for future exploration missions.

4. List of Acronyms

ATV – Automated Transfer Vehicle
CEV – Crew Exploration Vehicle
CL – Cis-Lunar

CPS – Cryogenic Propulsion Stage
DMS – Deimos
DRA – Design Reference Architecture
DRM – Design Reference Mission
EML – Earth-Moon Lagrangian point
EML1-HAB – Habitat in EML1
HAB-SM – Habitat in EML1 Service Module
HEO – High Earth Orbit
HSE – Human Space Exploration
IMLEO – Initial Mass in Low Earth Orbit
ISRU – In Situ Resources Utilization
ISS – International Space Station
LEO – Low Earth Orbit
LLO – Low Lunar Orbit
LOX – Liquid Oxygen
MAV – Mars Ascent Vehicle
MEO – Medium Earth Orbit
MIT – Massachusetts Institute of Technology
MO – Moon Outpost
MOr – Mars Orbit
MP – Mars Preparation
MS – Moon Sortie
NEA – Near Earth Asteroid
NTR – Nuclear Thermal Rocket
PMM – Permanent Multipurpose Module
S/C – Spacecraft
SEP – Solar Electric Propulsion
RvD – Rendezvous and Docking

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