A methodology for innovative technologies roadmaps assessment to support strategic decisions for future space exploration.

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Maria Antonietta Viscio [a], Eugenio Gargioli [b], Jeffrey A. Hoffman [c], Paolo Maggiore [a], Andrea Messidoro [a], Nicole Viola [a]

[a] *Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy*
[b] *Thales Alenia Space Italy, Strada Antica di Collegno 253, Torino 10146, Italy*
[c] *Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*

E-mail addresses: maria.viscio@polito.it (M.A. Viscio), eugenio.gargioli@thalesaleniaspace.com (E. Gargioli), jhoffma1@mit.edu (J.A. Hoffman), paolo.maggiore@polito.it (P. Maggiore), andrea.messidoro@gmail.com (A. Messidoro), nicole.viola@polito.it (N. Viola)

Travelling beyond LEO is the next step in the conquest of the solar system and so far, a human expedition to Mars is considered the most interesting goal of the future Human Space Exploration (HSE).

Due to the technological and operational challenges associated to a human mission to the Red Planet, it is necessary to define an opportune path of exploration, relying on many missions to intermediate and "easier" destinations, which would allow a gradual achievement of the capabilities required for the human Mars mission.

According to the actual interest in this topic, a study was carried out with the aim of defining a HSE reference scenario and analyse the relative technological issues.

The reference scenario was built considering as final target the human mission to Mars as defined by NASA DRA 5.0. The intermediate destinations were selected so that they will guarantee the implementation and achievement, through a step-by-step approach, of all the capabilities required to accomplish the human mission to Mars. All the scenario destinations' missions were analysed and characterized in terms of strategies, architectures and needed building blocks. Then specific analyses concerning the key technologies to accomplish those missions were performed, starting from the definition of a large database collecting the most innovative and not yet space qualified technologies up to the analysis of how the most important ones are implementable through the various destinations and missions elements.

The obtained results are represented by a versatile tool, useful to support strategic decisions, allowing understanding and visualizing where, when and in which elements each technology can potentially be applied and tested (maybe at limited extent), before being implemented in a specific mission where it is absolutely required. This could be very helpful to well place investments in the development of specific systems to allow future space exploration missions.

The paper, after an overview of the HSE reference scenario and of the process followed to build it, focuses on the description of the methodology defined to build a tool for technologies roadmaps assessment. Specific examples are provided to better explain how the tool can be exploited.

Keywords: human space exploration, key technologies, deep space missions, strategic decisions tool.

1. Introduction

Space exploration has always been a fascinating topic and today several studies are being carried out to determine the most significant next steps for human expansion through the Solar System [1, 2, 3]. So far, a human mission to Mars is considered the most exciting and interesting goal. However, due to the big challenges associated to this type of mission, it is essential to define an appropriate path to follow, which guarantees a gradual achievement of all the capabilities needed for the manned mission to Mars [4, 5, 6, 7].

There are several technological limitations that have to be overcome to get ready for a long and far human mission to the Red Planet surface. For this reason an accurate analysis needs to be performed, in order to identify which are the required technologies and evaluate how they can be implemented and tested in easier and closer deep space destinations missions to be then available for the final Mars mission.

These topics were addressed in the frame of MITOR 2012 Project, which was a collaboration program established in 2012 between Politecnico di Torino (Department of Mechanical and Aerospace Engineering – DIMEAS) and Massachusetts Institute of Technology (Department of Aeronautics and Astronautics – MIT

AeroAstro) and dealing with the theme “Human Space Exploration: from Scenario to Technologies”*. Basically the project activities went from the definition of a human exploration reference scenario to the identification of the technologies needed to accomplish the scenario’s missions [8]. In particular, the scenario was built considering as final goal a human mission to Mars by the end of 2030s as conceived by NASA “Human Exploration of Mars: Design Reference Architecture 5.0” [9]; all intermediate destinations’ missions were identified and characterized according to the NASA mission’s features.

Aim of this paper is the description of the process followed for the assessment and analysis of the technologies required to accomplish a human mission to Mars, through a progressive implementation in intermediate destinations. A specific tool was developed and the methodology adopted to build it is described in details, focusing on the various steps that have been followed along the analysis. The tool represents a versatile means to support strategic decisions for future space exploration of different targets, being particularly useful to assess where, how and when it is possible to gradually implement innovative technologies to achieve the capabilities required for more and more challenging missions.

Many references can be found in literature dealing with the issue of exploration enabling technologies, which report roadmaps according to the plans of space agencies [10, 11, 12, 13, 14, 15, 16]. The innovative aspect of the work presented in this paper is related to the tool that has been built to support strategic decisions for human space exploration and particularly to the methodology that has been defined to build such a tool.

The tool provides a database of innovative technologies and allows identifying where, how and when they are needed and/or implementable according to a reference human space exploration scenario. It is the result of a versatile methodology, which can be easily extended to other reference missions.

Differently from other works available in literature, the present work analyses were based on a pure technical approach, as costs were not taken into account. In fact the considerations behind the scenario and the tool derive from the analysis of the capabilities needed to gradually expand the human presence through the solar system, not taking into account costs issues. Strategic decisions for space exploration roadmaps are certainly based on both technical and cost considerations but are also 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.

The tool that has been built for the technologies assessment and the related methodology, that is the main topic of this paper, represent only a part of the MITOR 2012 Project outcomes. However, in order to have a clearer understanding of the issue, in section “2. Human Space Exploration Reference Scenario” a brief overview of the reference scenario and how it was built is reported. Then section “3. HSE Technologies” reports a detailed discussion about the tool that has been developed, focusing on the adopted methodology and summarizing the obtained results. Furthermore, examples of how the tool can be used are reported as well. Eventually in section “4. Conclusions” main conclusions are drawn.

2. Human Space Exploration Reference Scenario

2.1. HSE Scenario

The first part of the MITOR 2012 Project was devoted to generate a reference Human Space Exploration (HSE) scenario, setting as final target the human mission to Mars as defined by NASA DRA 5.0 [9]. This mission was always taken as reference and the scenario was built in such a way that it guarantees as much as possible a step-by-step approach in the achievement of the capabilities required for Mars.

The process went through several steps, starting from the identification and selection of the intermediate deep space destinations to the definition of the missions’ architectures and the assessment of their relevant building blocks [17]†.

Several intermediate destinations missions’ concepts were defined, deriving from the combination of very high level concept attributes [8] (some details are provided in Appendix A). For these concepts a “capabilities analysis” was carried out, leading to the selection of the six most relevant ones to guarantee the achievement of the capabilities required for the final Mars mission [8].

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* 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

† The analysis of the missions’ trajectories was out of the scope of this study. However it is worth underlining that several works are available in literature, which could be used as reference to perform this type of evaluations [18, 19].

The analysis started from the identification of Mars required capabilities, analysing the mission elements envisaged by NASA DRA 5.0. A "capability" is basically a function that is likely to be implemented in a subsystem of an element and that can be considered critical since it requires one or more not yet fully space qualified technologies, new and challenging design solutions or never implemented and challenging operations (e.g. "in space multiple dockings"). Then, starting from the capabilities list derived for Mars, a specific analysis was carried out, to verify their applicability on all identified intermediate destinations concepts; as result a matrix was produced ("capabilities map") showing the mapping of the capabilities (both required and applicable[‡]) on the various destinations and according to the concepts characteristics. Fig. 1 shows the obtained "capabilities map": the cells are red, blue or white according to the corresponding capabilities (listed in the first columns), which are respectively required, applicable or not applicable to a specific mission concept.

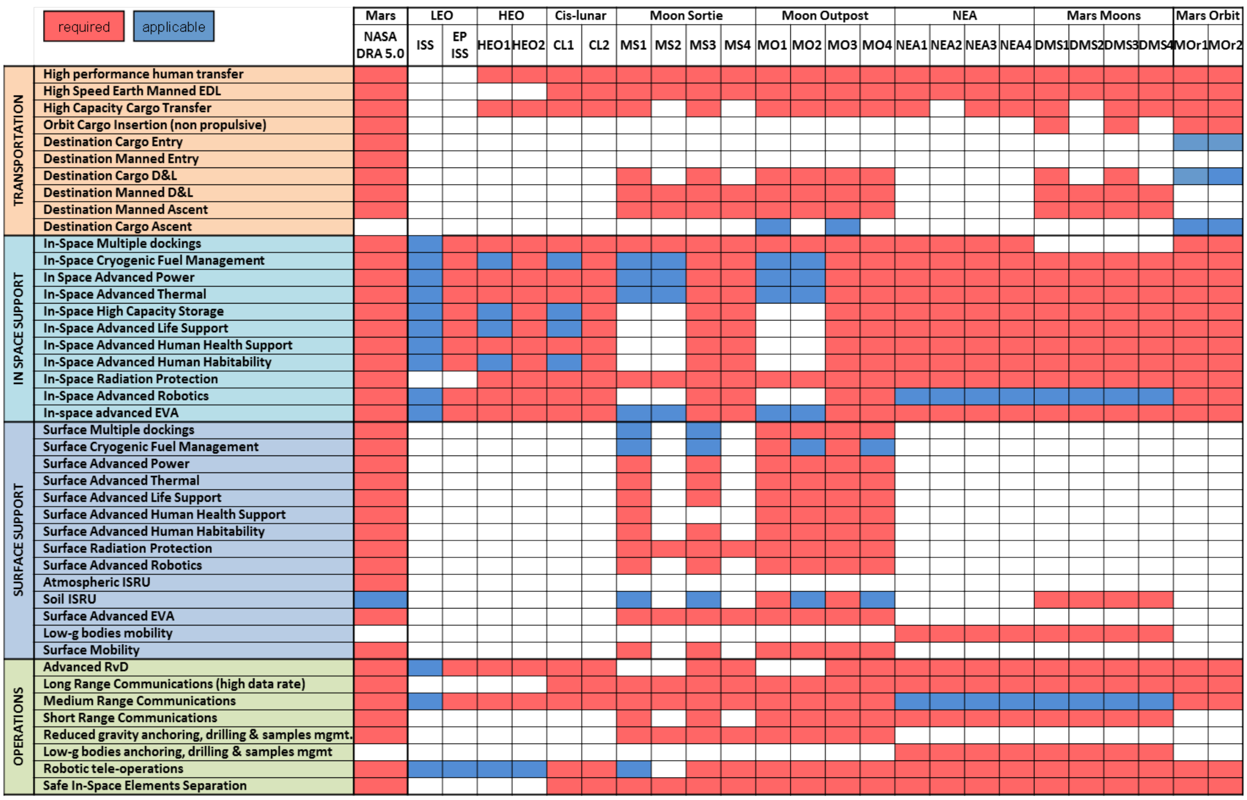

Fig. 1: Capabilities Map

Starting from this matrix the minimum number of destination concepts that allow the demonstration and achievement of the Mars required capabilities in intermediate locations (where they can be required or applicable) was determined. Specifically, the selected destinations concepts are:

- ISS, that includes several demonstration missions, exploiting the already available infrastructure;
- Cis-lunar (concept 2), that foresees missions to the first Earth-Moon Lagrangian point (EML1), and considered because of the deep space environment, the "easy" accessibility to/from Earth and the possibility of an increased science return from the Moon, as well as support to human activities on the Moon [20];
- Moon Sortie (concept 3), which includes several sortie missions in various locations on the Moon surface, all relying on the support of the cis-lunar station;
- Moon Outpost (concept 3), which is envisioned for building up a lunar outpost on the surface of the Moon and performing a rehearsal of the Mars mission surface phase [21];

[‡] "Required" means enabling or highly impacting on the overall mission/architecture, while "Applicable" is used to indicate that it is possible to be implemented and achieved at the specific destination, even if not strictly needed.

- NEA (concept 1), that includes a human mission to an asteroid, which represents a significant mission, with analogous Mars mission deep-space aspects but much closer than Mars [22, 23, 24, 25];
- Mars Preparation, which is an additional concept (not shown in the matrix) introduced to achieve specific capabilities needed for the human Mars mission and not achievable in any other destination; it includes several robotic missions to Mars surface.

The six destinations concepts were analysed in details, starting from the definition of a general strategy, which describes the different phases of the concept, proceeding with the assessment of the number and type of missions, and finally ending with the definition of the missions' architectures and concept of operations. The overall result was a HSE reference scenario including quite a large number of missions (both human and robotics). Moreover, all the elements needed to accomplish those missions were identified and characterized [8]. It is worth underlining that the considerations about the elements came from the idea to have as much as possible a stepwise enhancement through following destinations (see sub-section "2.2 HSE Scenario Elements Summary" and Appendix B for additional details about the elements needed for the reference missions through the scenario destinations). In this regard, a specific "commonalities analysis" was performed to verify that the same-class elements, implemented in successive destinations, were able to satisfy more and more demanding requirements, thus guaranteeing a gradual improvement in their performance (some details are provided in Appendix C).

The reference scenario that was finally obtained is shown in Fig. 2, in which all the missions are indicated along the temporal reference window (2014-2039). The graph has to be read starting from the bottom, i.e. the ISS concept, up to the top, referring to the Mars mission concept (NASA DRA 5.0). The "star" envisaged in 2039 (top right corner) represents the final human mission to Mars.

Each destination area is divided in more rows, referring to the different phases of the mission concept, according to the defined strategy [8].

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 cargo delivery, those labelled with a *pink M* are crew exploration missions and those labelled with a *yellow U* are unmanned logistics missions. Finally, already planned robotic missions are also included in the scenario (in *blue*).

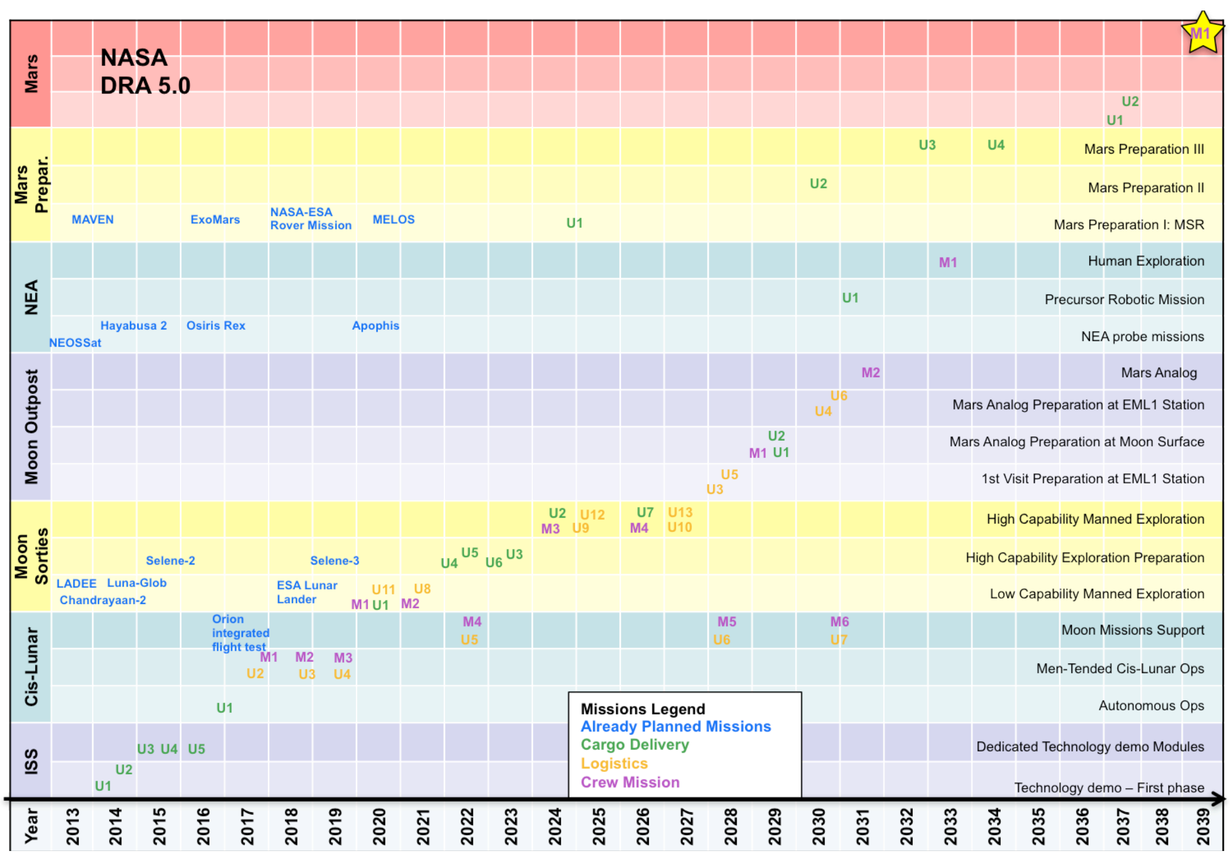

Fig. 2: Human Space Exploration Reference Scenario

2.2. HSE Scenario Elements Summary

As addressed before, for each mission included in the scenario, the relative architecture and concept of operations were analysed [8]. Furthermore, an assessment of the needed elements, as derived from the architectures analysis, was performed. The description of these aspects is out of the scope of the present paper, which instead focuses on the methodology followed for the definition of a technology roadmaps assessment tool. However a synthetic overview of the obtained results is provided in Table I.

Destination Concept	**Elements**		
	Transportation	**In Space**	**Surface**
ISS	-	-	-
	• Space Tug	• ATV-like module • PMM-like module	-
	• Cryogenic Tank Demo • NTR demo	• Inflatable demo	-
Cis-Lunar	• Space Tug	• Robotic Arm (ERA-like)	-
	• Cryogenic Propulsion system • Small NTR	• Logistics Module	-
	• EML1-HAB Service Module • Crew Exploration Vehicle (CEV) • CEV Service Module	• Cis-lunar Habitat • Airlock	-
Moon Sorties	• Small NTR • Space Tug • Crew Exploration Vehicle (CEV) • CEV Service Module	• Logistics Module	-
	• Big Manned Lander • 8-tons lander	-	• Small Exploration Rover • Unpressurized Rover • Pressurized Rover
	• 1-ton lander • Small Manned Lander • Small LH2 tank	• Fuel Tank • Lunar Relay Satellite	• Precursor Rover • Utility Cart • Manipulator • FSPS Demo • SolPS • ISRU Demo • Pressurized Rover Demo • Small Traverse Caches • Airlock + EVA Systems • Suit Ports + EVA Systems
Moon Outpost	• Small NTR • Small LH2 tank • Space Tug • Crew Exploration Vehicle (CEV) • CEV Service Module	• Fuel tank • Logistics Module	• SolPS • Pressurized Rover • Airlock + EVA Systems • Suit Ports + EVA Systems
	• Short term NTR • 23-tons lander	-	• Manipulator • FSPS • Small ISRU Plant • Traverse Caches
	-	-	• Lunar Surface Habitat • Lunar Communication Terminal
NEA	• Small LH2 tank • Space Tug • Crew Exploration Vehicle (CEV) • CEV Service Module	• Suit Ports	-
	• Small NTR-enhanced • Long Term NTR	• Deep Space Habitat	-
	• Drop Tank • MMSEV	-	-
Mars Preparation	• Long Term NTR	-	-
	• Interplanetary Space Tug • 2-tons lander • 20-tons lander	• MSR ERV • MSR Orbiter • Mars Relay Satellite	• MSR Rover • Utility Cart • Manipulator

	• Descent/Landing Stage • Medium Aeroshell • Aeroshell • MAV Demo • LH2 Tank		• SHAB Demo • FSPS • SolPS • Atmospheric ISRU Plant
	• Small Aeroshell • MSR Mars Ascent Vehicle	-	• Atmospheric ISRU Demo

Table I: HSE Scenario Elements Summary: red, yellow and green cell colours refer to *"new project"*, *"upgraded version"* or *"already used"* elements, respectively.

Table I reports a summary of all the elements through all intermediate destinations (for a synthetic description of the elements please refer to Appendix B). The list of elements for each destination derived from the detailed analysis of the concepts of operations for the various missions of the reference scenario (please refer to [8] to understand how the missions architectures have been derived). The definition of the elements was done taking as reference ESA and NASA studies [9, 26, 27, 28, 29, 30, 31, 32, 33, 34].

In Table I, the elements are grouped in cells having different colours to indicate if the element is a "*New Project*" (red cells), an "*Upgraded Version*" (yellow cells) or an "*Already Used*" element (green cells) with respect to the previous step.

From Table I it can be seen that there is a gradual improvement in the elements utilization, according to the philosophy behind the study. For example, if you 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.

3. HSE Technologies

The second part of MITOR 2012 Project aimed at identifying the innovative and promising not yet fully space qualified technologies and determining their applicability on the elements of the proposed reference HSE scenario. The final goal was however the implementation of a flexible tool applicable to different final destinations (not only to the proposed scenario), in order to support strategic decisions for future space exploration specifically in terms of technologies roadmaps.

This part of the work, with all the relevant analyses and assessments, tried to answer the following questions:

- What are all the technologies that can be implemented in the future HSE missions?
- In which HSE missions/elements these technologies are absolutely required?
- In which HSE missions/elements these technologies could be implemented and tested?
- What are the most required and applicable technologies?

The methodology that was defined and implemented to build the tool is shown in Fig. 3. The box on the left side of Fig. 3 represents the evaluation of the HSE reference scenario (as briefly introduced in the previous section), which is an input for the definition of the technologies roadmaps tool (right side of Fig. 3).

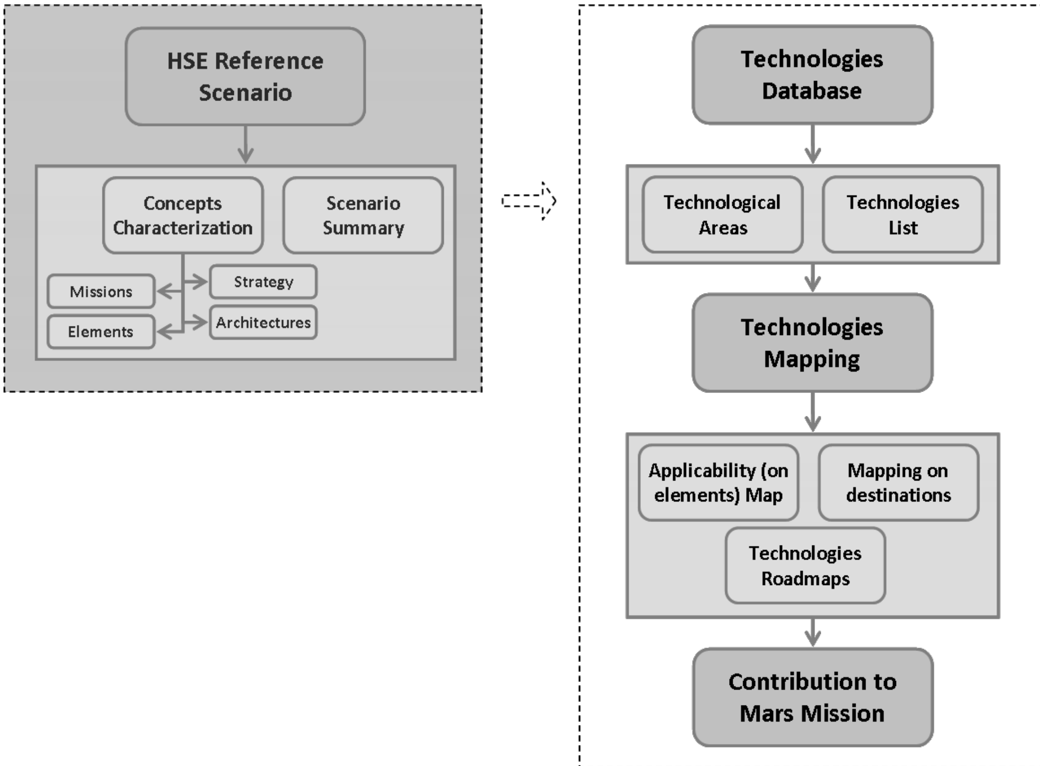

Fig. 3: Methodology for the definition of the technologies roadmaps tool

The process started from the development of a Technologies Database. The most important and innovative technologies were identified, by means of an accurate review of the major space agencies recent documents on capabilities and technologies assessments and roadmaps [9, 10, 35, 36, 37, 38, 39, 40]. Quite a detailed database was built, in order to collect a large number of innovative technologies grouped in technological areas and sub-areas.

Then a technologies mapping was carried out, including three main steps. First, an applicability map was developed to map the technologies on the elements of the reference scenario. Then, the technologies were mapped on the destinations of the scenario. Finally, a list of the "most required" technologies was derived, showing when and in which mission elements each technology is needed (technologies roadmaps).

As last step of the process, the level of contribution of each mission concept to the demonstration of technologies needed for the reference Mars mission was evaluated.

In the following sections, a thorough description of all these steps is reported, providing also some examples to allow a better understanding of the process.

3.1. Technologies Database

The first step of the process aimed at building the technologies database, which is an organized list of innovative technologies that were ordered according to specific technological areas.

In order to group the technologies, eleven Technological Areas (TAs) were considered. Technological Areas can have a direct correspondence with subsystems:

- TA.1 Structures and Mechanisms
- TA.2 Power
- TA.3 Thermal
- TA.4 Robotics and Automation
- TA.5 Avionics
- TA.6 Communications
- TA.7 Attitude, GNC
- TA.8 Life Support

- TA.9 Propulsion[§]
- TA.10 Environment, Humans and Safety
- TA.11 Atmospheric Descent and Landing

Each TA was further decomposed into relevant Technological Sub-Areas, corresponding to a specific function/subsystem: a summary of all the eleven TAs and the relative sub-areas is shown in Fig. 4.

TA.1 Structures, Mechanisms & Separations	**TA.5 Avionics**	**TA.9 Propulsion**
1.1 Structure	5.1 Avionics	9.1 Chemical
1.2 Mechanisms		9.2 Electric
1.3 Separations	**TA.6 Communications**	9.3 Nuclear Thermal
	6.1 Communications	9.4 Electromagnetic
TA.2 Power		
2.1 Power Generation	**TA.7 Attitude & GNC**	**TA.10 Environment, Humans & Safety**
2.2 Power Distribution & Management	7.1 Attitude	10.1 Radiation Protection
2.3 Energy Storage	7.2 Guidance & Navigation	10.2 Reduced Gravity
	7.3 Control	10.3 Dust Mitigation
TA.3 Thermal		10.4 Habitability
3.1 Thermal Control	**TA.8 Life Support**	10.5 EVA
3.2 Thermal Protection	8.1 Air Management	10.6 Crew Health
3.3 Cryogenic Systems	8.2 Water Management	10.7 Fire Detection & Suppression
	8.3 Waste Management	
TA.4 Robotics & Automation	8.4 Food Management	**TA.11 Atmospheric Descent & Landing**
4.1 Sensing & Perception	8.5 Hybrid Processes	11.1 Atmospheric Descent
4.2 Mobility, Support & Anchoring		11.2 Landing
4.3 Manipulation & Capture		
4.4 Human-Machine Interface		
4.5 Cognition		
4.6 Autonomy		

Fig. 4: Technological Areas and Sub-Areas

The technologies were listed according to these Sub-Areas and could eventually be grouped in Technical Categories, which include more technologies (e.g. Advanced Rigid Structure category). Furthermore, for each technology several variants can be specified.

An example of this classification is reported in Table II, which specifically refers to the "TA.1 Structures and Mechanisms". For this TA, three sub-areas were considered, which are "Structures", "Mechanisms" and "Separations", and for each of them a certain number of technologies were identified.

The same process was followed for all the eleven TAs and at the end quite a large database was obtained, collecting the most innovative technologies.

Technological Sub-Area	Technologies	Name/Variants
1.1 Structures		
Advanced Rigid Structures	Advanced Al Alloy Structures	Al-Li Alloy
		Al-Ti Alloy
		Al-Sc Alloy
	Other Metals Structures	Titanium
	Advanced Composite Structures	Al MMC
		Al Honeycomb
		Graphite epoxy resin
		Thermoplastic

[§] Please note that only chemical and nuclear propulsions are considered, mainly based on the reference NASA DRA 5.0, which actually does not foresee solar electric propulsion. This point could be further addressed especially for what concerns the robotic missions (including the Mars ones) [41].

	Open Cells Resin Foams Structures	BASF Melamine - Basotect
	Advanced Deployable Structures	Ultra-light Rigid
		Flexible
	Multifunctional Structures	Rigid
		Flexible
	Smart Nano-Structures	
	Pressurized Inflatable Structures	
	Boom & Modular Structures	
	Advanced Secondary/Tertiary Structures	Flexible Bags
	Structures Health Monitoring and Control Techniques	Self Healing Structures
		Advanced Techniques
1.2 Mechanisms		
Docking Mechanisms	**In-space Advanced Docking Mechanisms**	Unmanned Docking Systems
		IBDM/iLIDS/NDS
	Surface Docking Mechanisms	
Generic Mechanisms	**Low-cyclic Deploying Mechanisms**	
	Low-cyclic Extension Mechanisms	
	High cyclic Long Life Pointing Mechanisms	
	Low Speed Surface Deployment Mechanisms	
Specific Mechanisms	**Sampling Mechanisms (Drilling, Collection)**	
1.3 Separations		
Separation	**Advanced Pyrotechnique Separations**	Low-shock
	Non-explosive Separations	
	Hot Structures Separations	

Table II: TA.1 Structures, Mechanisms & Separations

3.2. Technologies Mapping

The second step of the process was the mapping of all identified technologies on the reference scenario [42]. In particular, as introduced with the methodology shown in Fig. 3, the technologies mapping was characterized by three major steps: it started from the mapping on the elements of the scenario (applicability map), then it proceeded with the mapping on all destinations and eventually it ended with the most required technologies roadmaps.

Hereafter, the description of the process is reported, together with specific examples. The methodology adopted, which indeed represents the focus of the paper, is easily extendable to other cases.

3.2.1 Applicability Map

Once the database had been completed, an "applicability analysis" was performed to verify in which HSE missions/elements the identified technologies are absolutely required or can be anyway implemented and tested.

This analysis consisted of a mapping of the technologies on the HSE reference scenario elements, performed per classes of elements. As explained in Appendix C, in the "Elements Commonalities Analysis" the elements were grouped in 16 classes of elements, which include similar elements satisfying more and more demanding requirements. In Appendix C, an example is discussed to illustrate how the requirements are defined and how the complexity increases through successive destinations elements.

Specifically, the objective of the "applicability analysis" was to build for each elements' class a matrix describing the mapping of the technologies on the elements, considering that, with respect to an element, a technology can be:

- required, if enabling or significantly impacting on the overall mission/architecture;
- applicable, if possible to be implemented, even if not strictly required;
- demo, if it can be implemented as a demo while being required for a following mission;

- not applicable, if not possible to be implemented.

Not all the identified technologies were mapped on the elements, and specifically 83 (out of about 160) were selected (the technologies reported in bold font in Table II are those selected for the "TA.1 Structures and Mechanisms"): they were considered the most significant ones mainly because of their effective growing potential and their actual TRL (technologies with very low TRL (TRL<2) and for which more interesting alternatives do exist were discarded[**]). Of course all the technologies required for Mars were taken into account.

Fig. 5 provides the reader with an example of how the "applicability analysis" was carried out. This example refers to the "Long Permanence Habitat" class, which includes the following elements (grouped in "surface" and "in space"):

- Surface elements
    - Big Manned Lander (BML), that is a manned lunar lander envisioned to host four crew members up to 180 days (Moon Sortie concept);
    - Lunar Surface Habitat (LSH), envisaged to support a crew of six astronauts for 540 days permanence on the Moon surface (Moon Outpost concept);
    - Surface Habitat Demo (SHAB Demo), which is a demo module to demonstrate long duration habitability (540 days) on Mars surface (Mars Preparation concept);
    - Mars Surface Habitat (SHAB), that is the habitation module envisaged for the Mars crew mission to host six astronauts for 540 days [7];
- In Space elements
    - Inflatable Demo, which is a demo module to be attached to the ISS for several months to demonstrate the inflatable technology;
    - EML1 Habitation module (EML1-HAB), that is a pressurized module to be deployed in the first Earth-Moon Lagrangian point (Cis-Lunar concept) and capable to host four astronauts for a permanence of 180 days [26, 27, 28];
    - Deep Space Habitat (DSH), that is the habitat to be used in the further exploration missions (NEA concept and Mars mission) [22, 23, 24].

[**] Having TRL<2 means that the technology development has not started yet [43] and this implies quite large uncertainties on its implementation. For this reason, other alternatives were preferred to those technologies with such low TRL.

		Surface				Space		
TA	Technologies	Big Manned Lander (BML)	Lunar Surface Habitat (LSH)	SHAB Demo	Mars Surface Habitat (SHAB)	Inflatable Demo	EML1-HAB	Deep Space Habitat (DSH)
1.1	Advanced Rigid Structures	Red	Blue	Blue	Blue	White	Blue	Blue
	Advanced Deployable Structures	Blue	Red	Blue	Red	White	Blue	Blue
	Pressurized Inflatable Structures	Blue	Red	Yellow	Red	Red	Red	Red
	Boom & Modular Structures	Blue	Red	Yellow	Red	Red	Red	Red
	Advanced Secondary/Tertiary Structures	Red	Red	Yellow	Red	Yellow	Red	Red
1.2	**In-space Docking Mechanism (IBDM/iLIDS/NDS)**	Red	White	White	White	White	Red	Red
	Surface Docking Mechanisms	Red	Red	Yellow	Red	White	White	White
	High cyclic Long Life Pointing Mechanisms	Blue	Red	White	Red	White	Red	Red
	Non-explosive Separations	Blue	Blue	Blue	Blue	White	Blue	Red
2.1	Flexible Solar Arrays	Blue	Red	Blue	Red	White	Red	Red
	High Efficiency Solar Cells	Blue	Red	Yellow	Red	White	Red	Red
2.3	Advanced Regenerative Batteries	Blue	Red	Yellow	Red	White	Red	Red
	Regenerative Fuel Cells	Blue	Red	Yellow	Red	White	Red	Red
3.1	Advanced MLI	Blue	Red	Red	Red	Yellow	Red	Red
	High-T Heat Pump	Blue	Red	Yellow	Red	White	Blue	Blue
	2-phases Heat Transfer	Blue	Blue	White	Blue	White	Blue	Blue
	Advanced Radiator	Red	Red	Yellow	Red	Yellow	Blue	Blue
4.2	Dexterous Manipulators	Blue	Blue	Yellow	Blue	White	Blue	Blue
8.1	**ARES**	Blue	Red	Yellow	Red	White	Red	Red
	Artificial Photosynthesis	Blue	Blue	Yellow	Blue	White	White	White
	Regenerative TCC Systems	Blue	Red	Yellow	Red	White	Red	Red
8.2	UV/Visible Photocatalysis	Blue	Red	Yellow	Red	White	Blue	Blue
	Brine De-watering	Blue	Red	Yellow	Red	White	Blue	Blue
8.3	Advanced Waste Compacting Systems	Blue	Red	Yellow	Red	White	Red	Red
	Advanced Waste Processing Systems	Blue	Red	Yellow	Red	White	Red	Red
8.4	Liofilization	Blue	Red	Yellow	Red	White	Red	Red
	FCU	Blue	Red	Yellow	Red	White	Red	Red
10.1	**Advanced Shielding Materials**	Red	Red	Yellow	Red	Yellow	Red	Red
	Advanced Shielding Concepts	Blue	Blue	Yellow	Blue	White	Blue	Blue
10.3	**Advanced Outside Dust Mitigation**	Red	Red	Yellow	Red	White	White	White
	Advanced Inside Dust Mitigation	Red	Red	Yellow	Red	White	White	White
10.6	**Inflatable Airlock**	Blue	Blue	White	Blue	White	Red	White
	Mobility Jet Pack (MMU)	White	White	White	White	White	Yellow	White
10.7	In-flight Surgery	White	White	White	Blue	White	Yellow	Red

Fig. 5: Technologies Applicability on Elements – Long Permanence Habitat

The matrix illustrated in Fig. 5, according to the colour of the cell, indicates if the listed technologies are required (red), applicable (blue), demo (yellow) or not applicable (white) on the various elements belonging to the considered class.

The assessment of the "applicability" was performed by considering some reference designs [9, 26, 27, 28, 29, 30, 31] or some assumed requirements for the elements. This is particularly true for the required technologies, while the applicable, demo and not applicable technologies mainly relied on evaluations of similar elements or on considerations about the environment and the type of module (e.g. the reference design does not foresee a specific technology, which anyway could be implemented on the module according to the mission it has to accomplish). For example the inflatable demo element is a module envisaged to validate the inflatable technology, which is indeed a required technology (i.e. pressurized inflatable structures); however some additional technologies could be included as demo on the module (e.g. advanced secondary/tertiary structure).

Analogously to what described for the "Long Permanence Habitat" class, the applicability analysis was carried out for all the other 15 elements classes, and for each of them a similar matrix was produced.

These obtained matrices represent the starting point to proceed with the mapping on the destinations of the reference scenario.

3.2.2 Mapping on intermediate destinations

Once the mapping had been completed for all the elements classes, and 16 matrices had been produced, the required and applicable technologies were mapped on the various destinations of the HSE scenario. Eventually, by summarizing and processing the obtained results, it was possible to rank the most required technologies, thus generating the so-called technologies roadmap.

For each destination, the elements that need a certain technology were counted, in order to have a clearer view of which are the most required technologies. All required technologies were taken into account. Analogously, the applicable technologies were addressed to have a summary of which and how many elements could potentially be exploited to validate these technologies before their actual implementation.

As an example, Table III and IV summarize the mapping of the "TA.1 Structures and Mechanisms" technologies, respectively required and applicable technologies throughout the HSE scenario.

Table III refers to the required technologies, which are ordered starting from those required in the largest number of elements. The numbers reported in the cells indicate the number of elements requiring the specific technology for each destination concept; moreover, the total number of elements on the whole scenario is specified. Finally, the first time the technology is needed is highlighted, showing both the first element of the scenario in which it shall be implemented (column "1st Element") and the year when it is required for the first time (column "Year").

Required Technologies	HSE Destinations/Concepts							Total		
	ISS	CL	MS	MO	NEA	MP	Mars	#	1st Element	Year
In-Space Advanced Docking Mechanisms	2	4	5	4	5	3	7	30	ATV-like	2014
Advanced Secondary/Tertiary Structures		3	5	5	4		7	24	EML1-HAB	2017
Advanced Rigid Structures		1	3	2	1	5	5	17	CEV	2018
Advanced Pyrotechnique Separations		2	3	3	4	1	4	17	CEV	2018
Advanced Deployable Structures		1	2	4	1	2	4	14	CEV-SM	2018
High-cyclic Long Life Pointing Mechanism		1	1	2	3	1	3	11	EML1-HAB	2017
Low-cyclic Deploying Mechanisms			1	2	1	3	4	11	SolPS	2022
Non-Explosive Separation Mechanisms	1				1	2	5	9	PMM-like	2014/15
Boom & Modular Structures	1	2		1	1		3	8	Inflatable Demo	2015
Pressurized Inflatable Structures	1	2		1	1		3	8	Inflatable Demo	2015
Low-speed Surface Deploying Mechanism			2	1		3	1	7	1-ton lander	2022
Surface Docking Mechanisms			3	2			2	7	PR-Demo	2023
Sampling Mechanism			3	1				4	1-ton lander/SER	2022
Hot Structures Separations						3	1	4	Small Aeroshell	2024

Table III: Required Technologies Mapping on HSE scenario destinations – TA.1 Structures and Mechanisms

Similarly, Table IV reports for each destination the elements in which the specific technology can be implemented as applicable technology, specifying the total number for each destination, as well as showing the total number of elements on the whole scenario (the most significant elements are highlighted as well).

Note that the numbers indicated in both tables do not include recurrent units.

Applicable/DEMO Technologies	HSE Destinations/Concepts							Total
	ISS	CL	MS	MO	NEA	MP	Mars	#
In-Space Advanced Docking Mechanisms						MAV Demo		1
Advanced Secondary/Tertiary Structures	ATV-like, PMM-like, inflatable demo	LM	2	LM		SHAB Demo	1	9
Advanced Rigid Structures	ATV-like,PMM-like,NTR demo	6	17	12	8	14	13	73
Advanced Pyrotechnique Separations			Fuel Tank, LRS	2	1	8	1	14
Advanced Deployable Structures		EML1-HAB	5	1	1	9	3	20
High-cyclic Long Life Pointing Mechanism			1-ton lander, BML					2
Low-cyclic Deploying Mechanisms			3					3
Non-Explosive Separation Mechanisms	ATV-like	EML1-HAB	BML	LSH	Drop Tank	5	2	12
Boom & Modular Structures			5	2		4	3	14
Pressurized Inflatable Structures			5	2		1	2	10
Low-speed Surface Deploying Mechanism			SML, BML					2
Surface Docking Mechanisms						SHAB Demo		1
Sampling Mechanism			8-tons lander, precursor rover			2-tons lander		3
Hot Structures Separations								

Table IV: Applicable Technologies Mapping on HSE scenario destinations – TA.1 Structures and Mechanisms

In the same way of what has been described for the "TA.1 Structures and Mechanisms", the mapping of technologies on the intermediate destinations can be derived for all the technological areas, thus obtaining an overall mapping of the technologies on the whole scenario.

These tables are very useful to visualize when each technology is required the first time, and identify the possibilities to previously implement and validate it in other destinations. Moreover, they can be a support to decide where it is more urgent and/or convenient to place investments, considering the due dates and the number of missions and elements requiring the technologies.

3.2.3 Technologies Roadmaps

As result of the just discussed mapping, a ranking of the most interesting and critical technologies can be done. For example, referring to the example here discussed of the "TA.1 Structures and Mechanisms", a new In-space Advanced Docking Mechanism is required in numerous missions and the first possibility to use it is in an ATV-like cargo mission to the ISS in 2014. Advanced Secondary/Tertiary Structures are needed for CL, MS, MO, NEA and Human Mars Mission concept, but they can be implemented and tested in simpler missions to ISS prior to 2017. Analogous considerations apply to Advanced Rigid Structures, applicable to quite a large number of elements. Concerning separations, Advanced Pyrotechnique Separations are required in a lot of elements, starting with the CEV in 2018. They are also applicable to a large set of units, especially in the Mars Preparation concept.

Similar considerations can be drawn for all the other technological areas and finally an overall ranking of the most required technologies can be derived, with information about the time and elements in which each technology is needed. The obtained results represent a good support for the identification of the most critical technologies to be developed, highlighting also the timeframe in which they are needed. This could be very helpful, in order to well place investments in the development of specific systems necessary to allow future space exploration missions.

In particular, Table V summarizes the 30 most required technologies, highlighting the number of elements in which each technology is required, the year when it is needed the first time, the first mission concept in which it is required and relative concept implementing it, according to the HSE reference scenario.

Technology	**Technological Area**	**# of elements**	**Needed Time**	**1st Mission Concept**	**First Element**
LIDAR	TA.4	37	2014	ISS	ATV-like
In-Space Advanced Docking Mechanisms	TA.1	30	2014	ISS	ATV-like
Advanced Outside Dust Mitigation	TA.10	24	2022	MS	Utility Cart

Advanced Secondary-Tertiary Structures	TA.1	24	2017	CL	EML1-HAB
Advanced Cryo-transfer Concept	TA.3	23	2018	CL	Small NTR
HDA Algorithm	TA.7	22	2022	MS	1-ton Lander
Stereo Vision 3D Camera	TA.4	18	2018	CL	Small NTR
Advanced Shielding Materials	TA.10	17	2016	ISS	NTR Demo
Advanced Pyrotechnique Separations	TA.1	17	2018	CL	CEV
Advanced Rigid Structures	TA.1	17	2018	CL	CEV
Advanced MLI	TA.3	17	2017	CL	EML1-HAB
Advanced PCU	TA.2	16	2022	MS	SolPS
Advanced Radiators	TA.3	16	2022	MS	Manipulator
High-Efficiency Solar Cells	TA.2	13	2017	CL	EML1-HAB
Surface Mobility Algorithm	TA.7	13	2022	MS	Utility Cart
RG Algorithm	TA.7	11	2022	MS	1-ton Lander
Regenerative Fuel Cells	TA.2	10	2017	CL	EML1-HAB
Advanced Inside Dust Mitigation	TA.10	10	2023	MS	PR Demo
Advanced LBO-ZBO Concepts	TA.3	10	2020	MS	SML
NTR Fission Reactor-NERVA like	TA.9	9	2016	ISS	NTR Demo
Pressurized Inflatable Structures	TA.1	8	2015	ISS	Inflat. Demo
Pumped-fed LOX/LCH4	TA.9	7	2020	MS	SML
Advanced Surface Locomotion	TA.4	7	2022	MS	Utility Cart
Pressure-fed Storable MON(NTO)/MMH	TA.9	6	2018	CL	CEV-SM
ARES	TA.8	5	2017	CL	EML1-HAB
Regenerative TCC Systems	TA.8	5	2017	CL	EML1-HAB
Advanced Waste Compacting Systems	TA.8	5	2017	CL	EML1-HAB
Lyophilisation	TA.8	5	2017	CL	EML1-HAB
Food Complement Unit (FCU)	TA.8	5	2017	CL	EML1-HAB
Advanced Water/Surface Airbags	TA.10	5	2018	CL	CEV

Table V: Transversal Ranking of Required Technologies

The timeframes in which all the technologies are needed derived from all the considerations done for the reference scenario missions and shall be read as “desired dates”. The complete set of results obtained from the just discussed analysis is helpful to support technologies developments strategic decisions and can answer the questions about the most required/applicable technologies for the whole scenario or for a single destination. Moreover the tool gives information about when a technology shall be ready and in this respect could provide an input to define an adequate development plan.

Just as an example of how to use the tool, consider as target the cis-lunar concept and consider the technology “Advanced Secondary-Tertiary Structures”. This technology is required in three elements of the cis-lunar concept and specifically the first time it is needed is in 2017 in the EML1-HAB (see Table III and V). However, looking at Table IV, it appears clear that this technology can be previously implemented and tested at the ISS (in one of the elements foreseen for the ISS concept like the ATV-like module, PMM-like or inflatable demo). This type of consideration can be done for all the technologies needed for the cis-lunar concept, thus allowing the definition of an opportune roadmap for those technologies, in terms of their development and implementation in “easier” missions to validate them prior to the cis-lunar missions.

Starting from these results, further analyses could be devoted to the evaluation of interdependencies between technology development activities.

3.3. Technological Contribution to Mars mission

In this section, the potential contribution of each intermediate destination concept of the reference scenario to NASA DRA 5.0 is briefly discussed.

Each intermediate destination can contribute to the achievement of the technological capabilities required for Mars in different percentage considering technologies required or anyway applicable at the specific destination.

Table VI summarizes the number and the percentage of Mars required technologies which, in each intermediate destination, are:

- required,
- applicable/demo,
- applicable/demo or required,
- not applicable.

The percentages have been evaluated considering that 64 technologies in total are required for Mars, according to the NASA DRA 5.0 concept [7].

Analysed Concepts	**Technologies**							
	Required		Applicable/Demo		Required or Applicable/Demo		Not Applicable	
	#	[%]	#	[%]	#	[%]	#	[%]
ISS	7	10,9	24	37,5	28	43,8	36	56,2
Cis-lunar	30	46,9	22	34,4	37	57,8	27	42,2
Moon Sortie	38	59,4	48	75,0	56	87,5	8	12,5
Moon Outpost	48	75,0	24	37,5	53	82,8	11	17,2
NEA	35	54,7	18	28,1	41	64,1	23	35,9
Mars Preparation	36	56,3	52	81,3	61	95,3	3	4,7

Table VI: Destination Concepts Contribution to NASA DRA 5.0

These data were obtained starting from the mapping tables developed for all the technological areas (built analogously to what described in the previous section, where only the example of "TA1. Structures and Mechanisms" has been discussed – Tables III and IV).

For each destination, the total number of required and applicable technologies was derived, which was then expressed as a percentage of the Mars required technologies. Table VI also indicates the percentage of "required or applicable/demo", that refers to the technologies that can actually be implemented at the specific destination.

The graphs reported in Fig. 6, 7 and 8 graphically summarize the obtained results for the intermediate destinations, showing the percentages of Mars required technologies that are required or applicable in the intermediate concepts.

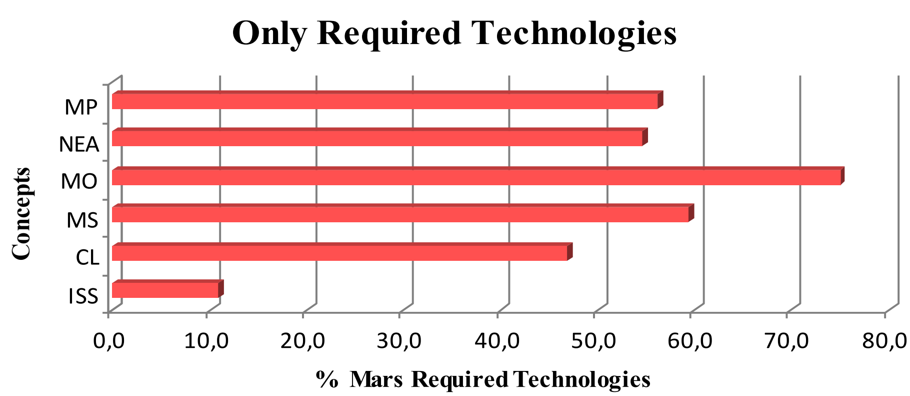

Fig. 6: Percentage of required technologies to implement in intermediate destinations

From Fig. 6 it is evident that Moon Outpost requires 75% of the technologies required for Mars. It is followed by Moon Sortie, Mars Preparation and NEA. As foreseeable the ISS does not require many new technologies, and specifically the resulting 11% refers to the technologies needed for the new modules part of the ISS concepts (and not to the already deployed ISS modules).

Considering the applicability/demo of the technologies through the intermediate destinations (graph in Fig. 7), the Mars Preparation concept represents the best test-bed with more than 80% of the Mars required Technologies. The Moon Sortie concept is also a good option to implement technologies needed for Mars (75%).

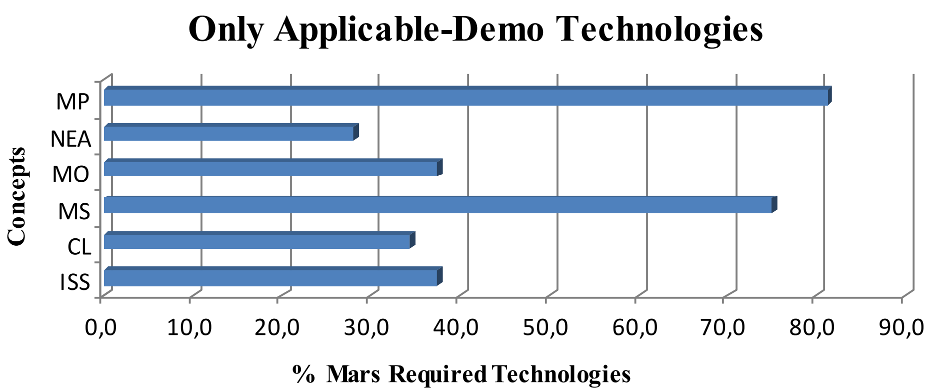

Fig. 7: Percentage of applicable technologies to implement in intermediate destinations

Finally, the last graph (Fig. 8) provides the resulting percentage of technologies that are required or applicable at the specific destination.

It is worth underlining that a specific technology can be required for an element while applicable to another element of the same destination concept (this explains why the "Applicable/Demo or Required" value is not given by the sum of the only "Required" and the only "Applicable/Demo" values). For example, if you consider the cis-lunar concept and the technology "Advanced Deployable Structure", this technology is required in one element, that is the CEV-SM (Table III), but is also applicable to the EML1-HAB (Table IV). In this case, when counting the total number of technologies, it is counted as one in both the "required" and "applicable" categories, but it is counted only once in the "Applicable/Demo or Required" category (and not two as it would be by summing the "required" and "applicable" values). The same types of considerations were done for all the other technologies.

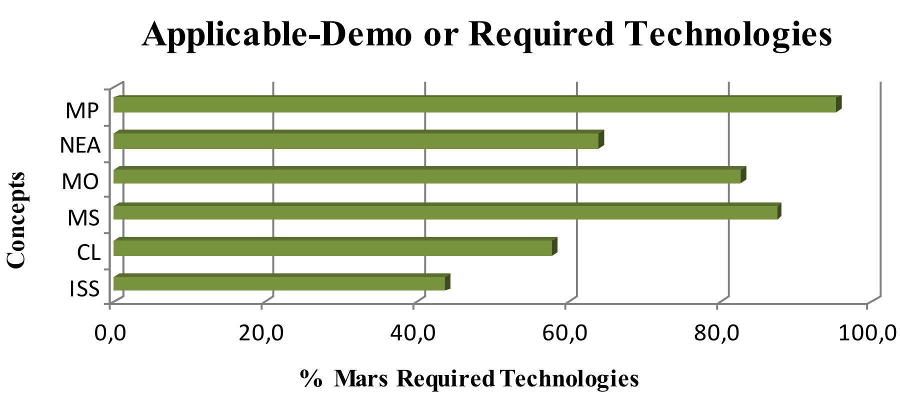

Fig. 8: Percentage of required or applicable technologies to implement in intermediate destinations

This last graph (Fig. 8) is the one that best highlights the contribution of each destination to the achievement of the technological capabilities required for Mars. As a matter of fact, it refers to the actual number of technologies which can be validated at the destination, being them either required or applicable.

The MITOR 2012 project outcomes and, in particular, the graphs just discussed can be exploited to take strategic decisions in support of future human space exploration. Indeed, looking at the technologies implementable in the various intermediate destinations, it is possible to have indications of which are the most interesting destinations for future deep space exploration, according to the final objective of a human mission to Mars.

For example, the lunar concepts (Moon Sortie and Moon Outpost) are better test-beds than NEA for what concerns the Mars required technologies.

Moreover, as conceivable, the ISS concept does not require many Mars required technologies, but a large percentage of them (37.5%) is applicable there. In total, more than 43% of the technologies required for Mars are implementable (required or applicable) at the ISS where they can be tested and validated, without the need of new infrastructure or other location in space. On the basis of this result a very important conclusion can be drawn, in terms of strategic decisions: the operative life of ISS shall be extended as much as possible, in order to fully exploit its potential capabilities in the framework of future human space exploration.

Furthermore, the analyses results show that the Cis-lunar concept can be a significant alternative to the NEA exploration, in terms of demonstration of Mars required technologies, even if they are not actually equivalent.

However an expedition to an NEA is still a very interesting mission, since it gives the opportunity to perform a Mars-analogue mission, at least for what concerns the deep-space travel, with limited complexity. This will be very important especially for psychological issues and astronauts training. Finally, a NEA mission would have many other scientific objectives that can be coupled with the technological demonstration ones.

4. Conclusions

The paper presents the results obtained in the frame of MITOR 2012 Project, developed as collaboration between Politecnico di Torino and Massachusetts Institute of Technology, and dealing with the topic "Human Space Exploration: from Scenario to Technologies".

The first objective of MITOR 2012 Project was the definition of a reference scenario for future space exploration, having as final target a human expedition to Mars by the end of 2030s. In order to progressively achieve the capabilities required for Mars (according to the NASA DRA 5.0 mission) through incremental steps, six intermediate destinations concepts are included in the 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.

The second part of the project was dedicated to the identification and assessment of innovative technologies enabling the future missions beyond LEO. The paper focuses on this topic, describing the methodology adopted to build a tool for technologies roadmaps assessment in support of strategic decisions for space exploration. The obtained results and examples of how to use the tools are discussed as well.

Identifying the most required technologies, which today limit the possibility to move forward in the exploration of the solar system, is a topic of interest of many industries, agencies and academic institutions [9, 39]. Moreover, once identified, it is very important to understand how to implement these technologies through several incremental steps, in order to test and validate them in less risky missions, thus improving our knowledge to get ready for more challenging targets. This was the main reason why the topic was addressed in the frame of the MITOR 2012 Project, whose final results were indeed quite a detailed database describing the most innovative technologies, a tool to understand the level of applicability (required, applicable/demo) to various missions' elements, at several deep space destinations and in specific timeframes, and the methodology to build such a tool, which can easily be followed to extend the analyses to other cases.

As largely discussed, the results presented in the paper derived from the assumption of a final human mission to Mars as defined by the NASA DRA 5.0, and the last graphs shown in Fig. 6-8 specifically refer to this mission.

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 a Mars Human mission as final target.

As also addressed in [9], 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 therefore 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 for the identification of the needed technologies and to support the definition of opportune development roadmaps.

According to this, even if a different "easier" architecture or a different time opportunity (maybe a postponed time opportunity), were considered for the final mission to Mars [44], the considerations done in this study, and most of all the methodology developed, would still be valid and applicable.

Furthermore, the methodology adopted in the definition of the tool is still valid if a different final target is considered, and in this regard the tool can be used as reference set of the most innovative and enabling technologies, for which their applicability to scenario elements is specified, to support decisions about future missions to whatever deep space destination of the solar system, up to a Mars mission.

For example, considering as target a cis-lunar mission, the technologies required for that destination are identified; moreover the tool allows verifying if each technology can be implemented in a previous mission, i.e. at the ISS. According to this information, it is possible to define an opportune roadmap for the technology in terms of its development and implementation on "easier" missions to validate it and have it ready for the cis-lunar missions.

Finally, the obtained results are a good support to identify the most critical technologies that need to be developed, highlighting also the timeframe in which they are needed. This could be very helpful in order to well place investments in the development of specific systems in order to allow future space exploration missions.

The evaluations presented in the paper were all based on a pure technical approach, as no costs considerations were done. However, the analysis could be further developed to cover budgeting issues, and in particular to evaluate both development and recurrent costs.

Starting from the obtained results, and specifically from the technologies listed in table V, as first step the actual TRL of the technology shall be assessed, in order to determine its development plan according to the time when it is needed (the development costs will be driven by this plan). Moreover, the total number of elements, which will implement the technology, will be a parameter to take into account for the cost assessment (recurrent costs).

5. List of Acronyms

ATV – Automated Transfer Vehicle
BML – Big Manned Lander
CEV – Crew Exploration Vehicle
CEV-SM – CEV-Service Module
CL – Cis-Lunar
DMS – Deimos
DRA – Design Reference Architecture
DSH – Deep Space Habitat
EML – Earth Moon Lagrangian point
EML1-HAB – Habitat in EML1
EP-ISS – Equatorial Post-ISS
ERA – European Robotic Arm
ERV – Earth Return Vehicle
ESA – European Space Agency
EVA – Extra Vehicular Activity
FCU – Food Complement Unit
FSPS – Fission Surface Power System
GNC – Guidance Navigation and Control
HDA – Hazard Detection and Avoidance
HEO –High Earth Orbit
HSE – Human Space Exploration
IBDM – International Berthing and Docking Mechanism
iLIDS – International Low Impact Docking System
ISRU – In Situ Resources Utilization
ISS – International Space Station
LBO – Low Boil Off
LCH4 – Liquid Methane
LEO – Low Earth Orbit
LH2 – Liquid Hydrogen
LIDAR – Laser Imaging Detection and Ranging
LM – Logistics Module

LOX – Liquid Oxygen
LRS – Lunar Relay Satellite
LSH – Lunar Surface Habitat
MAV – Mars Ascent Vehicle
MLI – Multi Layer Insulation
MMSEV – Multi Mission Space Exploration Vehicle
MO – Moon Outpost
MOr – Mars Orbit
MP – Mars Preparation
MS – Moon Sortie
MSR – Mars Sample Return
MT – Megatons
NASA – National Aeronautics and Space Administration
NEA – Near Earth Asteroid
NDS – NASA Docking System
NTR – Nuclear Thermal Rocket
PCU – Power Control Unit
PMM – Permanent Multipurpose Module
PR – Pressurized Rover
RG – Relative Guidance
RvD – Rendezvous and Docking
S/C – Spacecraft
SER – Small Exploration Rover
SHAB – Mars Surface Habitat
SML – Small Manned Lander
SolPS – Solar Power System
TA – Technological Area
TCC – Trace Contaminant Control
TRL – Technology Readiness Level
ZBO – Zero Boil Off

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APPENDIX A

The main features of the intermediate destinations "Candidate Concepts" are provided in Table A.1. The concepts are described through high level attributes.

Destination	Candidate Concept	Main Features
LEO	ISS	• Permanent crew • Long Permanence (more than two weeks) • Research & technologies test lab
	Equatorial Post-ISS	• Equatorial Post-ISS • Men-Tended • Long Permanence (more than two weeks) • Research Lab & Exploration Spacecraft assembly
MEO/HEO	HEO1	• HEO • Men-Tended • Short Permanence (up to two weeks) • Research & techs test lab
	HEO2	• HEO • Men-Tended • Long Permanence (more than two weeks) • Exploration S/C assembly
Cis-lunar	CL1	• EML1 • Men-Tended • Short Permanence (up to two weeks) • Research laboratory
	CL2	• EML1 • Men-Tended • Long Permanence (more than two weeks) • Exploration S/C support
Moon Sorties	MS1	• Direct Approach • Long Stay (more than two weeks) • Long Exploration Range (several km from landing site) • Pre-Deployed Cargo
	MS2	• Direct Approach • Short Stay (a few days) • Short Exploration Range (up to 1 km from landing site) • All up Cargo
	MS3	• Staging in cis-lunar • Long Stay (more than two weeks) • Long Exploration Range (several km from landing site) • Pre-Deployed Cargo
	MS4	• Staging in cis-lunar • Short Stay (a few days) • Short Exploration Range (up to 1 km from landing site) • All up Cargo
Moon Outpost	MO1	• Direct Approach • Men-Tended • Long Stay (between 250 and 600 days) • Long Exploration Range (up to 150 km from landing site) • Pre-Deployed Cargo
	MO2	• Direct Approach • Men-Tended • Short Stay (up to 180 days) • Long Exploration Range (up to 150 km from landing site) • Pre-Deployed Cargo

	MO3	• Staging in cis-lunar • Men-Tended • Long Stay (between 250 and 600 days) • Long Exploration Range (up to 150 km from landing site) • Pre-Deployed Cargo
	MO4	• Staging in cis-lunar • Men-Tended • Short Stay (up to 180 days) • Long Exploration Range (up to 150 km from landing site) • Pre-Deployed Cargo
NEA	NEA1	• LEO Departure • Pre-Deployed Cargo • No-landing • Exploration Vehicle for asteroid surface exploration
	NEA2	• LEO Departure • All up Cargo • No-landing • Exploration Vehicle for asteroid surface exploration
	NEA3	• Cis-Lunar Departure • Pre-Deployed Cargo • No-landing • Exploration Vehicle for asteroid surface exploration
	NEA4	• Cis-lunar Departure • All up Cargo • No-landing • Exploration Vehicle for asteroid surface exploration
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 A.1: Intermediate Destinations Candidate Concepts

APPENDIX B

In this appendix an overview of the elements part of the HSE reference scenario is reported. The elements here briefly presented refer to the intermediate destination missions and have been defined according to those required for the Mars mission (NASA DRA 5.0). They are reported in the three following tables, grouped into “Transportation”, “In-Space” and “Surface” categories.

Transportation	
• Cryogenic Tank Demo	Demo module for cryogenic fuel management on orbit.
• Cryogenic Propulsion system	Propulsive module using cryogenic propellant, adopted for short duration cis-lunar mission.
• NTR demo	Demo of nuclear thermal rocket.
• Small NTR	NERVA rocket – like nuclear stage with 24 MT maximum propellant capability
• Small NTR-enhanced	Evolution of the Small NTR to be used in a longer mission thus requiring a specific thermal control for propellant management
• Short term NTR	NTR with larger fuel loading capability (60 MT) and used for mission duration shorter than three months
• Long Term NTR	Evolution of the Short term NTR to be used in mission longer than three months (active thermal control for propellant management)
• EML1-HAB Service Module	Propulsive module for S/C injection in EML1 halo orbit and station-keeping.
• Crew Exploration Vehicle	Capsule to host astronauts mainly for the re-entry in Earth atmosphere
• CEV Service Module	Propulsive module attached to CEV
• Space Tug	Propulsive module to support elements transfers as well as RvD manoeuvres
• Interplanetary Space Tug	Propulsive module for interplanetary transfers of cargo (to Mars) in the Mars preparation concept.
• Small LH2 tank	Tank for LH2 short term storage having maximum loading capability of 25MT
• LH2 Tank	Evolution of the small LH2 tank with larger fuel loading capability (35MT)
• Drop Tank	Tank for the storage of LH2 (NEA mission) immediately released after the fuel is consumed.
• MMSEV	Multi Mission Space Exploration Vehicle to be used for the NEA proximity operations and to support EVA on asteroid surface
• 1-ton lander	Unpressurized lunar lander of 1 MT payload capability.
• Small Manned Lander	Manned landing conceived to support two crewmembers up to ten days
• 8-tons lander	Unpressurized lunar lander of 8 MT payload capability.
• Big Manned Lander	Manned landing conceived to support four Crewmembers up to 180 days
• 23-tons lander	Unpressurized lunar lander of 23 MT payload capability.
• 2-tons lander	Unpressurized Mars lander of 2 MT payload capability.
• 20-tons lander	Unpressurized Mars lander of 20 MT payload capability.
• Descent/Landing Stage	Stage analogous to that foreseen by NASA DRA 5.0
• Small Aeroshell	Small Aeroshell capable to decelerate limited masses (few tons) and performing only Aerocapture
• Medium Aeroshell	Aeroshell capable to decelerate larger masses (50 tons) and performing Aerocapture and entry manoeuvres
• Aeroshell	Large and human-rated aeroshell analogous to that foreseen by NASA DRA 5.0 (more than 100 tons)
• MSR Mars Ascent Vehicle	Vehicle for the Mars sample return mission
• MAV Demo	Demo of the Mars Ascent Vehicle to be used in the final human Mars mission

Table B.1 – Transportation Elements

In Space	
• ATV-like module	Pressurized module envisaged to carry to the ISS innovative technologies for their validation at the station.
• PMM-like module	Pressurized module envisaged to be attached to the ISS for the test of innovative technologies
• Inflatable demo	Demo module for validating at the ISS the inflatable technology
• Robotic Arm	ERA-like robotic arm
• Cis-lunar Habitat	Pressurized rigid-inflatable station deployed in EML1 to support the permanence of four crewmembers for up to six months. Envisioned as a staging post for Moon missions.
• Deep Space Habitat	Pressurized rigid-inflatable habitat to support a crew of four astronauts for mission duration of one year (NEA mission).
• Airlock	Rigid-Inflatable Airlock attached to EML1-HAB (designed for 6 EVA of 4 hours, for 2 crewmembers)
• Suit Ports	Systems envisaged to support the execution of EVA from the MMSEV
• Logistics Module	Logistics module foreseen for the re-supply of the cis-lunar station (resources + fuel)
• Fuel Tank	Tank for carrying and storing the fuel needed for the refuelling of the lunar landers.
• Lunar Relay Satellite	Orbital communication hub supporting Moon Sortie and Outpost missions at the South Pole location
• MSR Orbiter	Orbiter foreseen to support the surface activities during the MSR mission
• Mars Relay Satellite	Satellite conceived as an orbital communication hub during the human mission to Mars
• MSR ERV	Capsule envisioned to return samples on Earth in the Mars Sample Return mission

Table B.2 – In Space Elements

Surface	
• Precursor Rover	Small unmanned rover envisioned to investigate the south pole landing area, locate and prepare landing and surface assets sites and record following cargo and crew landings
• Small Exploration Rover	Unmanned rover to pre-explore areas before the crew surface traverse and to carry and deploy traverse caches.
• Unpressurized Rover	Unpressurized rover to support and extend the range of human exploration, carry and move payloads, tools and surface assets.
• Pressurized Rover Demo	Demo module to demonstrate long range and long duration surface exploration.
• Pressurized Rover (PR)	Pressurized rover to support human surface exploration allowing 100km range, and supporting two crewmembers, up to 14 days.
• Utility Cart	Unmanned system envisaged to move, deploy and set up surface assets
• SolPS	Element to provide primary power to the surface assets (Solar Power System)
• FSPS Demo	Demo element to demonstrate surface nuclear power production (Fission Surface Power System).
• FSPS	Fission Surface Power System to provide primary power generation to surface assets.
• Manipulator	Manipulator foreseen to offload surface assets from landers, install them on Utility Cart, change Utility Cart interfaces and tools and inspect landers and surface assets.
• ISRU Demo	Demo to demonstrate lunar soil ISRU, producing O2 and H20 (extraction, processing, storage, delivery).
• Small ISRU Plant	Plant for to the in situ production of propellant LOX and consumables O2, H20 (extraction, processing, storage, delivery)
• Atmospheric ISRU Demo	Demo to demonstrate Mars atmospheric ISRU, producing O2 and H20 (absorption, processing, storage, delivery)
• Atmospheric ISRU Plant	Plant for the in situ production of fuel (LOX) for Mars Ascent and, at small extent, consumables (O2, H2O, buffer gases).
• Small Traverse Caches	System to support local exploration during traverses far from landing site especially in emergency situations
• Traverse Caches	Larger system to support local exploration during traverses far from landing site especially in emergency situations
• Airlock + EVA Systems	Airlock to support EVA execution on the Moon surface (from BML or LSH)
• Suit Ports + EVA Systems	Conceived to support EVA execution on the Moon surface (from PR)
• Lunar Comms Terminal	Communication hub to support communications between surface assets and the cis-lunar station.
• Lunar Surface Habitat (LSH)	Pressurized habitat to support the permanence on the lunar surface of six crewmembers for 540 days.
• SHAB Demo	Demo module to demonstrate long duration (540 days) habitability on Mars surface.
• MSR Rover	Unmanned rover to investigate the landing area for Mars sample collection, collect and store 500 g of Mars sample and deliver it to the ascent vehicle

Table B.3 – Surface Elements

APPENDIX C

In this appendix the description of the "commonalities analysis" is 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.

The following 16 classes were considered:

- Nuclear Thermal Rocket
- Long Permanence Habitat
- Short Permanence Habitat
- Pressurized Modules
- Lander
- Surface Power
- Aeroshell
- Ascent Vehicle
- Earth Entry Vehicle
- Airlock and Suitports
- Space Tug
- Tank
- Surface Mobility - Rover
- ISRU
- Robotic Arm
- Communications Assets

Each class includes similar elements satisfying more and more demanding requirements, which correspond to gradually improving design and development efforts. An element can belong to more than one class depending on the analysed requirements (e.g. CEV in Short Permanence Habitat and Earth Entry Vehicle).

The analysis, carried out for each single class, was based on major high-level requirements (mission, functional, operational and interface). Hereafter, as an example, the nuclear thermal rocket class is discussed.

The Nuclear Thermal Rocket class 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 MT;
- **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 C.1 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

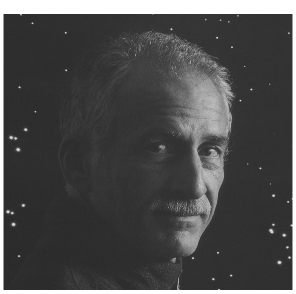
Fig. C.1: NTR Commonalities Analysis

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.

Maria Antonietta Viscio received a M.Sc. in Aerospace Engineering from University of Naples "Federico II" in July 2009. She attended the Post-Graduate Master in "SpacE Exploration and Development Systems (SEEDS)" at Politecnico di Torino, ISAE Toulouse and Universität Bremen working on the preliminary design of a NEA human exploration mission. She is currently a PhD student in Aerospace Engineering at Politecnico di Torino and Thales Alenia Space Italy. Her research activities focus on "Space Exploration Systems, Strategies and Solutions". She was visiting student at MIT from February to June 2012 working on "Human Space Exploration: from Scenario to Technologies" project.

Eugenio Gargioli is in the Aerospace business since 1986 and has been working in the last 10 years as chief engineer in the major Italian and European projects related to the International Space Station. He got his PhD in Hydraulic Engineering in 1985 in Rome and shortly after joined Thales Alenia Space Italia (formerly Aeritalia) in Torino. Eugenio Gargioli is currently appointed as End to End Space Infrastructure Systems Lead in the Business Section Space Infrastructures and Transportation.

Jeffrey Hoffman is Professor of Aerospace Engineering in MIT's Aeronautics and Astronautics Department. From 1978-1997 he was a NASA astronaut, making five space flights, becoming the first astronaut to log 1000 hours of flight time aboard the Space Shuttle and performing four spacewalks. Dr. Hoffman was Payload Commander of STS-46, the first flight of the US-Italian Tethered Satellite System. In August 2001, Dr. Hoffman joined the MIT faculty, where he teaches courses on space operations, space systems design, and space policy. He is director of the Massachusetts Space Grant Consortium, responsible for space-related educational activities. In 2007, he was elected to the U.S. Astronaut Hall of Fame.



Paolo Maggiore graduated in aerospace engineering at Politecnico di Torino. He is author of many technical papers regarding aerospace general systems, reliability, satellite testing integration and verification, logistics and design methodologies applied to space systems. At the present he is associate professor at Politecnico di Torino. His interests range from concurrent engineering to preliminary design methodologies applied to satellites, pressurized modules and exploration architectures; he is involved in studies of small electrical power generation units for space applications. The development of some applications on these subjects occurs in collaboration with Thales Alenia Space, ESA, ASI (Italian Space Agency) and Regione Piemonte. He is currently AIAA member.

Andrea Messidoro earned his MSc in Aerospace Engineering from Politecnico di Torino in 2011. During his studies, he spent one year at TU Delft, Netherlands. He attended an internship at the European Space Agency, in ESTEC, combined with his MSc thesis consisting of a feasibility study of a first human mission to a NEA. Since December 2011 he is research fellow at Politecnico di Torino, working on scenarios, strategies, missions, architectures, elements and technologies for Human Space Exploration (HSE). In 2012 he performed a study about HSE, within MITOR Project, collaboration between Politecnico di Torino and MIT, supported by Thales Alenia Space.

Nicole Viola has been working as Assistant Professor at the Department of Mechanical and Aerospace Engineering at Politecnico di Torino since March 2008. She had been working as Researcher on aeronautics and space systems design at Politecnico di Torino from April 2000. She got her PhD in Aerospace Engineering in 2004 on "Conceptual definition of transatmospheric and space vehicles". She is author of papers published on books, journals and international and national proceedings. Nicole Viola is currently teacher with tenure of the undergraduate course "On-board equipment and avionic systems" of the Aerospace Engineering degree.