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Using the ESA Exploration Technology Roadmaps in Support of New Mission Concepts and Technology Prioritization

Highlights

Sara Cresto Aleina, Nicole Viola, Roberta Fusaro, Giorgio Saccoccia, Valeria Vercella

- A tool for strategic, programmatic and technical decisions is studied;
- Logical processes are used to propose strategic choices;
- System Engineering and Decision Analysis are used to support the proposed methodology;
- A realistic case study is proposed: a lunar reference missions in the time frame 2020 to 2030;
- The main results of the proposed methodology application are there shown.

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Using the ESA Exploration Technology Roadmaps in Support of New Mission Concepts and Technology Prioritization

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Abstract: Exploration technology roadmaps have been developed by ESA in the past few years and the edition of 2015 has just been released. In the context of Moon exploration initiatives and using HERACLES mission as case study, the authors will apply methodologies studied to simulate technology roadmapping activities and technologies prioritization processes. In particular, the roadmaps for the procurement of technologies required for the HERACLES mission are here presented through its main building blocks.

Keywords: Roadmaps, Technology, Moon

1. INTRODUCTION

Exploration technology roadmaps have been developed by ESA in the past few years and the edition of 2015 has just been released. Scope of these technology roadmaps, elaborated in consultation with the different ESA stakeholders (e.g. European Industries and Research Entities), is to provide a tool for strategic, programmatic and technical decisions in support of the European role within an International Space Exploration context.

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 and associations [1, 2, 3, 4, 5, 6], deriving them with different procedures and features (Fig. 1). Almost all present roadmaps are based on interviews and are generally manually updated, but this kind of updating process deals with two main problems. Firstly, discussing with experts may create roadmaps able to support strategic decisions, but they are sometime limited by having single perspective that lacks in an integrated point of view capable of including all crucial elements beneath roadmaps.

Secondly, compiling and updating such roadmaps could become an overwhelming task only a few would be able to take on, due the continuous evolution of technologies and ideas regarding new mission concepts.

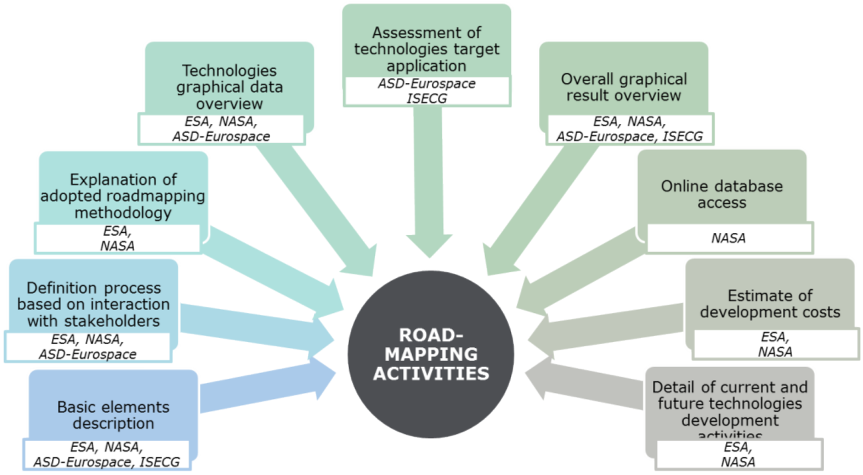

Fig. 1. Comparison between ESA, NASA, ASD-Eurospace and ISECG roadmapping activities.

To support the roadmapping process with a methodology able to fulfil these problems can lead faster to optimal results. Actually, the paper focus on a methodology developed to drive roadmaps' creation and update. Indeed, the innovative aspect of the work here presented lays in the methodology that has been developed to generate roadmaps to eventually support strategic decisions. The proposed methodology is intended to be flexible: the main aim of this work is not only to support the work on-going, especially at ESA, about the definition and the creation of technologies roadmaps, but it aims also at creating in a semi-automatic process the roadmaps themselves according to the user needs. The methodology is flexible enough to adapt to different type of users, which can be interested in looking specifically at one or more operational capabilities, technology areas, building blocks or mission concepts to increase Technology Readiness Level (TRL) or, more generally, to improve a particular kind of property in one or more elements between the one listed above.

In literature other methodologies to assess technology roadmaps for space exploration do exist [7, 8]. The main methodology implemented in [7, 8] is based on a database of technologies and allows identifying where, how and when they are needed and/or implementable according to a reference space exploration scenario such as [9]. Even if this approach leads to a versatile methodology, which can be easily extended to various reference missions, the tool does not pursue flexibility. Indeed, starting from the analysis of the OCs, the user has to move to MCs [10], BBs and eventually to technologies through a predetermined path. Even if this work was more technical and less related to programmatic aspects (e.g. costs analysis), a flexible and updatable methodology has been derived starting from this work, taking into account experts feedbacks and international roadmaps results [11, 12, 13].

In the context of Moon exploration initiatives, the paper will illustrate the use of the technology roadmaps to highlight the role of technology within Missions, Building Blocks and Operational Capabilities of relevance. Two years ago, ESA was supporting a specific lunar mission concept for robotic samples return, Human Enhanced Robotic Architecture and Capability for Lunar Exploration and Science (HERACLES) [14]. In particular, HERACLES mission focuses on designing a System of Systems (SoS) able to solve the mission objectives previously stated with multiple robotic missions to the lunar surface in preparation for human missions. Even if the proposed mission is not currently present between the top priorities for ESA, important building blocks and capabilities required for a lunar exploration and outpost are still present even if in a context that is simplified if compared to a Moon Village.

An updated version of the methodology for technology roadmap generation and management has been proposed for this case study. Indeed, while the previous methodology [11, 12, 13] was mainly based on market and stakeholders' requests, in this particular work the influence of stakeholders and market has been reduced in some rational and logical processes supporting it with System Engineering theories and tools [15, 16, 17]. In addition, a better delineation of demonstrative mission has been introduced. This updated methodology is the main subject of section 2, while the case study will be presented in section 3. Eventually main conclusions are drawn.

2. METHODOLOGY

In order to better support this activity, a logical sequence of actions that has to be performed to generate the roadmaps and the list of pillars and inputs that drive their creation have been studied. Consequently, an optimized methodology able to define and update technology roadmaps has been developed, pursuing a Systems Engineering approach and point of view [11, 18]. The methodology is flexible enough to support strategic decisions starting from different points of view (for instance the point of view of the developers of technologies, the systems designers or the mission concepts analysts), and it is based on a semi-automatic tool that exploits rational and logical procedures based on project management, system engineering and common sense applied in existing technology roadmaps generation process even if currently manually generated and updated.

Four are the pillars (or elements) of the methodology: Operational Capabilities, Technology Areas, Building Blocks and Mission Concepts. Starting from these elements and their interrelations technology roadmaps can be defined and analysed. For example, using an already defined roadmap a user may be interested in enhancing a group of elements related to a defined reference scenario, with a defined budget and a TRL to reach for every technology involved. Using as input the elements involved and their relationships, the proposed methodology allows a user perform this analysis through to set of inputs he can specify. Examples of inputs are related to the reference scenario as for the available budget, the TRL to reach, the launch date and the functions to perform (or the sub-systems to involve).

First of all, an *Operational Capability* (OC) is defined as a high level function (i.e. an activity) responding to a mission statement [11, 15] and allowing certain performances or results [18]. A list of OCs has to be derived selecting areas of high importance that have an influence on the development of technologies. In particular, considering the proposed case study, the selected OCs are those listed in ESA Space Exploration Technology Roadmap: Rendezvous and Docking With (Non) Collaborative Target (such as in [19]), High Capacity Cargo Transfer, Efficient Orbit Insertion and Maintenance, In-Orbit Refuelling, (Fast) Sustainable Human Flight and Cruise, Nuclear Energy Utilization, Entry Deceleration and Descent, Precision Soft Landing, Robotic/Tele-Robotic Surface Operations, Human Surface Habitability and Operations, In-Situ Resource Utilization, Surface Ascent and Return, Interoperability [1].

The second pillar of the methodology is the *Technology Area* (TA), which is a set of technologies that accomplish one or more OCs. In addition, a technology is considered as the result of the use of science and engineering based knowledge to meet a specific need (i.e. one or more specific OCs) [12]. As previously stated for OCs, also in this case, a list of TAs has been derived on the basis of ESA ones, considering the main current and future research areas and quantifying it according to the Technology Readiness Level (TRL) [20]. Indeed, TAs are strictly involved in the process aimed at finding the best path to increase TRL: technologies evolve when they are subjected to experimentation, refinement and increasingly validating tests. In addition to TRLs, other readiness indexes are considered in this analysis: Advancement Degree of Difficulty (AD2) [21] and Integration Readiness Level (IRL) [22]. The main relationship between these two indexes has been further analysed in [23]. According to [1], the considered TAs are: Life Support and Asset Protection, Novel Energy Production and Storage, Advanced Propulsion, Automation and Robotics, Thermal TPS (Thermal Protection System) And Aerothermodynamics Aspects, Advanced Structures and Mechanism Applications, GNC (Guidance Navigation and Control) And Related Sensors, Communications Remote Sensing and Imaging, Systems and Processes. It is worth remembering that every TA is split into “Technology Subject” and “Technology” sub-levels.

The third pillar of the methodology is the Building Block (BB), which is defined as a physical element that may include several technologies, combined together to achieve certain functions (OCs). The list of BBs, generally, exploits the concept of “modularity”, in order to simplify every BB to one or more specific elements. According to these definitions, a single BB can be considered as a system and slit into the sub-systems that this system may need to accomplish its main goals (Fig. 2). In this particular case study, being the main purpose of this paper to analyse the input coming from ESA space exploration roadmap to manage them in a proposal of new roadmap, this approach has not been analysed as in [11, 12, 13]. Indeed, in this case study, the considered BBs are: Tele-Robotic And Autonomous Control Systems, Rendezvous With Non-Cooperative Targets And Docking Systems, Storable Propulsion Modules And Equipment, Habitation Systems, Surface Mobility Elements, Sample Acquisition, Processing And Containment System, Visual Navigation, Hazard Detection And Avoidance, Sample Return Earth Re-Entry Capsule, Inter-Spacecraft Communication Systems, Advanced Landing Technologies For Mars, Miniaturized Avionics, Planetary Protection And Bio-Sealing, Ground Segment Elements [1].

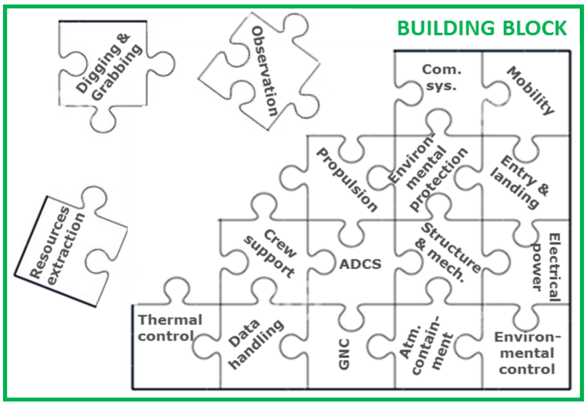

Fig. 2. Building Blocks composition concept.

Finally, the fourth pillar of the methodology is the *Mission Concept* (MC), which is defined through a mission statement and made up of BBs, implementing several OCs and making use of certain technologies. In particular in the definition of MCs are included both existing programmes and technology maturation activities. In this particular application, this group of pillar is considered as in the previous works [11, 12, 13].

The only difference that is worth mentioning is in how are considered the demonstrative missions. Indeed, from the point of view of mission objectives MCs can be categorized in: Operational Missions (i.e. missions that have been planned to reach scientific and/or technological objectives) and Demonstrative (Demo) Missions (i.e. missions that have been planned specifically to increase the TRLs of components/subsystems/system). The distinction between operational and demo missions can sometimes be tough, as rarely real missions can be considered totally operational or demo but most of the times missions can be defined in part operational and in part demo. In the latter case, in order to better portray and match reality, it is useful to express through percentage values how much of that mission can be accounted operational or demo, instead of looking at missions simply as either completely operational or demo [11, 12, 13]. It is worth noting that the presence of demo missions is fundamental to allow TRL increase. In the current methodology, at the end of the roadmap generation, all technologies related to one MC are analysed to estimate the percentage of them that in the specific MC are applied at low TRL values, i.e. those technologies that still have to be demonstrated through that mission (TRL equal or lower than 7 [23]). The percentage of these technologies (new and already applied ones) over the total amount of technologies applied is hereafter called "demo%": for sake of clarity, if "demo%" is 100%, the missions is a demonstrative, whereas if the "demo%" is 0%, the missions is operational.

Finally, an important feature to highlight is that every MC has properties that describe it. Examples of properties can be MC timing (i.e. launch date, starting and ending time), financial resources (i.e. resources amount and kind of funds used) and usual TRL allowed in that specific MC for the considered technologies. The list of MCs and their properties need to be continuously updated, both to take into account market developments or technological achievements and to support resources optimization.

As for the other pillars, the main goals of MCs are TRL increase and capabilities demonstration. As a consequence, it is easy to understand that the four main elements of the methodology (i.e. OC, TA, BB or MC) are strictly related one another, through a methodical process that, starting from any of the available elements, can suggest MCs and a suitable TRL increase (Fig. 3) and this interrelation is strictly connected to the Systems Engineering processes and tools. Indeed, the main aim of the methodology is to derive strategic decisions for future investments in TAs, regarding both their development and their demonstration to enable operational OCs or to enhance BBs through MCs. As Fig. 3 shows, depending on the user needs, the analysis can start from any element and then proceed along a predetermined path. For example, the user can start from the consideration of certain BBs, to move then to the required technologies to generate those BBs and eventually to the available MCs made up with the same BBs, defining also the OCs that are involved in the TRL increase. This flexibility of the tool is an important feature, to customize the technology roadmaps to the user needs [24]. One of the fundamental tools used in this methodology to link elements, describing the strict correlation between them, is the applicability analysis. The applicability analysis is here intended as a way to detect and picture a possible correlation between couples of elements coming from the four pillars. The applicability analysis highlights the connection between couples of elements and specifies the impact of every connection regarding stakeholders and market needs.

The applicability analysis is based on System Engineering tools and allows mapping one pillar of the methodology onto the others [11, 15]. In particular, four types of applicability analyses are here considered: applicability of OCs on TAs, applicability of TAs on BBs, applicability of MCs on TAs, and applicability of technologies on technologies (see Fig. 3). In the applicability analyses between different groups of pillars, the relationship between two elements is described by two labels (or no label at all): required (i.e. highly impacting relationship) and applicable (i.e. relevant but not strictly needed relationship). It is worth noticing that in this updated version, it is no more considered the “demo” label [11, 12, 13], this difference is due to the different definition of demonstrative missions during the process.

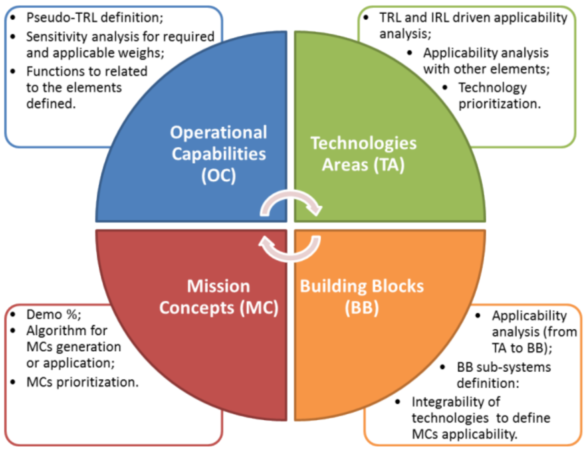

Fig. 3. Methodology for TRL increase through OCs, TAs, BBs and MCs.

To assign these labels to every couple of pillar from an objective point of view, a method related to Functional Analysis is applied [25, 26]. Considering how the four elements are derived and defined [27], it is possible to relate between them the various elements remembering the definition of possible sub-systems for the BBs. Having a comprehensive list of possible sub-systems, is then possible to relate them with the BBs (considering the ones that compose them), to the technologies (considering the technologies as elements of an increased level of detail compared to those sub-systems), to OCs (considering the functions that those sub-systems are able to perform) and, finally, to MCs (defining which of these sub-systems might be required for every single MCs and the functions that they perform). Therefore, a simple rule can perform a first draft assignment of these labels: the connection between two elements can be defined as “required” only if it has been already approved in [1], thus implying that the link has been considered as strictly necessary to satisfy final mission needs, as well as political, general public, economical, scientific and technological needs. Conversely, the connection between two elements can be defined as “applicable” if are all those combinations that have at least a sub-system “in common”. To the draft results obtained at this point, some considerations have to be added to reach final optimal results. Indeed, the “applicable” combinations at this point of the analysis are still a huge number because this method does not consider specific technological performances or features. The reason of this assumption is in the fact that, being the level of detail of this case study high, it is difficult to evaluate the performances of technologies under-development, but on the contrary, it is possible to specify some technology features in order to prune the combinations. In particular, two constraints are considered: the presence of interactions with human beings and the possibility to reach or be placed on a surface. Every element is then characterized with these two constraints. In case a mission scenario is defined as final target to reach, only the possible combinations of constraints are considered, remembering that the two constraints are not interrelated. In addition, if a constraint is not required for the reference scenario the elements related to it have to be considered only for "required" combinations (when not considering the applicability with MCs) and, considering MCs, only the case in which the MC has not the constraints but the element requires is impossible to use.

As specified in the previous list, the applicability with MCs is subject to different rules. This difference is related to the fact that if a MC is created with a particular feature does not means that this particular MC has to be rejected in the list of "applicable" cases. On the contrary, if an element has an undesirable feature it is unnecessary to propose additional combinations related to it. Additional considerations related to the reference scenario can be valued to reduce the number of applicable combinations. Indeed, a user can be interested in enhancing a specific group of sub-systems related with the reference scenario. The analysis has to be limited to these sub-systems in order to reduce the "applicable" combinations to the useful combinations.

Eventually, it is worth mentioning the applicability analysis of TAs on TAs. The possibility of validating more than just one single technology within the same mission is without any doubts a cost-effective approach that allows progressively increasing TRLs of crucial technologies while limiting cost rising. This applicability analysis is directly related to the IRL. Considering the IRL definitions is possible to define a scheme to relate current TRL for two technologies and the presence required and applicable combinations with BBs (considering the BBs that can be related to both the technologies) [23].

In the framework of the methodology, the applicability analyses are fundamental to map one pillar, specifically technologies, onto the others and to provide information about these connections (required or applicable) but further methods have been introduced, in order to rank technologies and build new missions. In particular, two kinds of trades' studies have been considered to rank the lists of technologies and MCs, thus assessing priorities respectively for technologies and MCs. This particular kind of trade study is introduced to correctly take into account the many elements into the TRL path increase estimation also considering the user inputs: indeed, if the user would specify a budget for the evaluation performed, it may happen that not all the technologies or the MCs can be founded. In addition, if there is any other kind of constraints (e.g. in the integration between required/applicable technologies in the same MC or BB or in the properties associated to the analysed pillars), having an ordered list of technologies and MC allows a prioritization between the possible combination that drives the roadmap generation or update to a feasible result.

As far as technology prioritization is concerned, important data for this trade study is to have a list of criteria defined. In particular, the following criteria have been applied: "most required technology over BBs" (i.e. the most used technology shall be addressed first, considering different weights if the technology itself is required or applicable) and "lowest TRL" (i.e. technologies with the lowest TRL shall be addressed first). Thanks to these criteria, the TRL increase can be achieved giving a high priority to the most applicable/required technologies.

A prioritization of MCs is required too. Indeed, considering the significant number of parameters (not only in the methodology elements, but also in constraints and properties), it is likely to have a huge number of combinations between MCs and technologies resulting in feasible combinations, but not all the combinations are required for the TRL increase path. To this purpose, Key Performance Indicator, KPIs, have to be introduced as prioritization criteria. Obviously, the MCs have to be ordered in a chronological order to avoid an incorrect choice in the TRL increase path. A second criterion considered is the "demo%", in order to consider first the MCs that allow a higher number of applicable combinations and a higher number of combinations with the considered technologies. Finally, as third criterion is considered the target environment of every MCs, in order to use first the MCs places in an environment nearest to the Earth, considering those MCs the ones that involve lower resources. Additional criteria are possible, customizing the analysis to the user needs.

Finally, referring to Fig. IV and starting from the intention of enhancing one or more technologies, the applicability analysis between OCs and TAs shows which capabilities are influenced by the chosen technologies. In particular it is necessary to define a quantitative parameter to express the current state of each OC. The parameter that has been introduced is called pseudo-TRL [11, 12, 13]. The pseudo-TRL can be obtained as follows for each OC A, linked to a required technology i (considered with a weight of r_i, equal to 1.5) and to an applicable technology j (considered with a weight of a_i, equal to 1):

$$pseudo - TRL_A = \frac{TRL_i + TRL_j}{r_i + a_j} \quad \text{where } r_i \geq a_j \tag{1}$$

At this point of the methodology, the main elements involved, as well as their properties, have been defined and analysed. Once this process is completed, all data need to be updated. This implies that pseudo-TRLs advance, mission scenarios progress, and technologies TRLs increase. Also the properties of BBs and MCs have to be updated if some improvements have been achieved. It is important to note that at the end of the methodology, information about TRL increase and its relationship with time are available. In particular, it is possible to estimate the time it takes to increase the TRL up to desired values, combining data about mission (e.g. time and budgets), data about tests to be performed and data about TRL increase.

3. RESULTS

Using HERACLES mission as case study, the authors have applied methodologies studied to simulate technology roadmapping activities and technologies prioritization processes. In particular, technology prioritization tools developed in support of the ESA Technology Roadmaps have been applied to two building blocks of relevance for HERACLES (i.e. Tele-Robotic And Autonomous Control Systems; Storable Propulsion Modules And Equipment), and one Operational Capability (i.e. Robotic/Tele-Robotic Surface Operations) and the results are here presented to highlight the approach for an effective TRL increase. The analysed example concerns the TRL increase in a set of TAs, in order to enhance these two BBs constraining the study on the specified OCs.

As already stated, the reference mission for this case study is HERACLES, an un-manned mission targeting the Moon. The main purpose of this mission is to demonstrate the key elements of a sustainable human exploration of the Moon and a human-robotic exploration of Mars by implementing lunar surface operations while providing science opportunities and programmatic content in the transition time at the end of ISS and after. The main features of HERACLES that can be considered as constraints for the proposed roadmap methodology are connected with schedule and the Concept of Operation (ConOps).

Having defined two BBs as starting point (i.e. Tele-Robotic and Autonomous Control Systems; Storable Propulsion Modules and Equipment) and the OC highlighted (i.e. Robotic/Tele-Robotic Surface Operations) will be considered as constraint at the end of the analysis to prune the final results. Therefore, we start from the defined BBs that we would like to enhance and we suggest a plan for the development of all technologies associated with these BBs. A plan for their development is then proposed, involving all the technologies, the capabilities and the missions connected to the chosen BBs. At the end of this analysis, an update of the elements involved and their properties has to be performed. Considering Fig. 3, once the BBs has been clearly identified and characterized, the TA (and TRLs) till the technology level can be mapped on them. Consequently, it can be derived a list of MCs and OCs that have a link with these technologies and with the starting BBs. A scheme of the methodology applied to the specific case study is shown in Fig. 4. Important constraints coming from the case study can be defined [14] and are reported in Tab. 1.

Tab. 1 HERACLES mission data.

Target environment	Moon
TRL to reach	8
Launch year	2024
BBs of interest	*Tele-Robotic And Autonomous Control Systems / Storable Propulsion Modules And Equipment*
OCs of interest	*Robotic/Tele-Robotic Surface Operations*
Analysed sub-systems functions	Structure and mechanism, electric power generation and management, thermal control, data handling, communication, attitude determination and control, guidance and navigation, propulsion, entry and landing, mobility, digging and grabbling and resources extraction

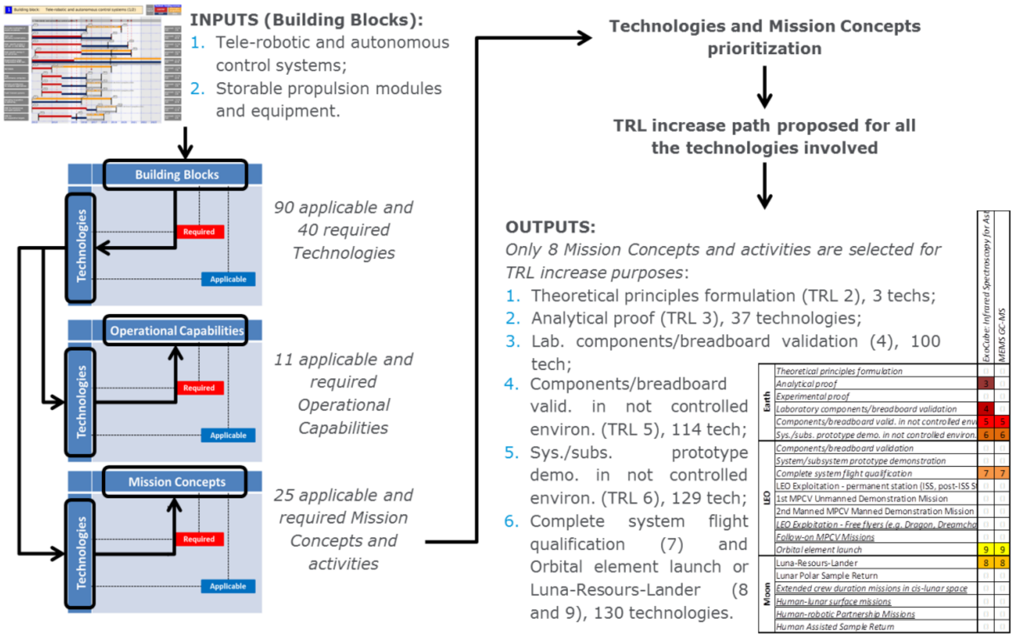

Fig. 4. Scheme of the case study application.

Following the methodology explained in the previous section considering these inputs it is possible to obtain all the data to define a technology roadmap (Fig. 4). In particular, following the applicability analysis, it is possible define a list of 130 technologies related to the starting 2 BBs, covering 9 TAs and divided into 90 applicable technologies and 40 required ones. These technologies are related to 11 OCs and 25 MCs. If we consider the Robotic/Tele-Robotic Surface Operations capability as constraint, these numbers are not reduced.

Due to the great number of MCs, some constraints and criteria are applied to prune the results, and eventually discuss the outcome of the work. The introduction of these constraints and criteria is due not only to the high number of MCs at this stage of the analysis, but also to the high number of inputs that are required for the TRL increase estimation. For example, technologies on technologies applicability analysis has to be considered in order to check if the selected technology can be integrated with the other technologies already in use in the listed MCs. For this analysis the experts' opinion is needed, not only for the huge number of combinations but also because detailed and specific information about every single technology is required and for this reason a simplified analysis is performed involving the IRL and few other constraints directly introduced from HERACLES reference mission (Tab. 1). Thank to this analysis is possible to find that no criticality has been underlined: no additional limitation to the number of available MCs has to be added.

In addition, two main logics add constraints to the analysis: the MCs prioritization process and the applicability analysis between technologies. Indeed, at this point we have a disordered list of both the elements, while ordered lists of MCs and technologies have to be defined to correctly choose the TRL increase path, according to industrial and rational priorities.

As a result, after the application of all these constraints, only some MCs are considered in the TRL increase path. Only 8 kind of Mission Concepts are selected for TRL increase purposes on Earth (i.e. Theoretical Principles Formulation, Analytical Proof, Laboratory Components/Breadboard Validation, Components/ Breadboard Validation In Not Controlled Environment, System/Subsystem Prototype Demonstration In Not Controlled Environment), in LEO (i.e. Complete System Flight Qualification, Orbital Element Launch) and on the Moon (i.e. Luna-Resours-Lander).

In order to update all the elements and their properties (e.g. the pseudo-TRL), the increase in the TRL has to be evaluated. For this reason, an attempt for a logical and semiautomatic procedure that will help the update for the TRL has been proposed, assuming a step by step approach in the TRL increase (i.e. one mission performed is equal to one additional level in the TRL). Of course this is particularly true for demo missions. In particular, the following list of MCs type to be proposed for the TRL increase path is derived:

1. Theoretical Principles Formulation activity, used to reach TRL 2 in 3 technologies;
2. Analytical Proof activity, used to reach TRL 3 in 37 technologies;
3. Laboratory Components/Breadboard Validation activity, used to reach TRL 4 in 100 technologies;
4. Components/Breadboard Validation In Not Controlled Environment activity that is used to reach TRL 5 in 114 technologies;
5. System/Subsystem Prototype Demonstration In Not Controlled Environment activity that is used to reach TRL 6 in 129 technologies;
6. Complete System Flight Qualification activity, used to reach TRL 7 in 130 technologies, proposed ad-hoc and with a final "demo%" value of 100%;
7. Luna-Resours-Lander programme, used to reach TRL 8 in 130 technologies, starting from a "demo%" of 74% and ending with the same value after the TRL 7 demonstrative mission.

In order to know in which percent the "old" MCs has been modified and in which way the results will affect the current state of the art, some parameters are proposed for a post-processing analysis (e.g. the "demo%" already listed before when influent and the "pseudo-TRL" values). Considering that in this particular case no information about the available budget were presented, all the technologies have been considered in the TRL increase path.

Looking at the results, it can be seen how, through the analysis of the four groups of pillars and a few other inputs it is possible to obtain an update of an existing roadmap (ESA Space Exploration Technology Roadmaps) to sustain a particular mission of reference (i.e. HERACLES). A clear example of this is in the final choice of MCs to apply. Indeed it can be seen how the methodology is able to choose in a MCs list and through a simple prioritization a final mission (i.e. Luna-Resours-Lander) really similar to the reference one. Indeed, this particular programme has a high priority, after less expensive activities on Earth and a demonstrative mission proposed to fulfil the TRL increase path.

Finally, talking about the Operational Capabilities enhancement a significant increase in the pseudo-TRL value can be appreciated. For example, looking at the constraining capability Robotic/Tele-Robotic Surface Operations, its starting pseudo-TRL was 3.13 considering the technologies under analysis and their current state. Updating the state of the technologies supposing to be able to fulfil the entire proposed roadmap, the final pseudo-TRL is 8. This high increase is related to the high number of technologies involved through the two BBs and to the fact that all these technologies where related to the OCs under analysis.

4. CONCLUSIONS

The paper presents the elaboration and rational justification of a logical methodology to generate technology roadmaps on the basis of System Engineering theories and tools, decreasing the stakeholders influence over the results. In the context of Moon exploration initiatives, the paper illustrates the use of the technology roadmaps to highlight the role of technology within Missions, Building Blocks and Operational Capabilities of relevance. In particular, using HERACLES mission as case study, the authors have applied methodologies studied to simulate technology roadmapping activities and technologies prioritization processes to two building blocks of relevance for HERACLES (i.e. Tele-Robotic And Autonomous Control Systems; Storable Propulsion Modules And

Equipment), and one Operational Capability (i.e. Robotic/Tele-Robotic Surface Operations) used as constraint and the results have been presented to highlight the approach for an effective TRL increase.

Applying the proposed methodology to the HERACLES mission case study, it can be demonstrated how it is possible to support roadmapping activities and prioritization processes and to derive important decision in a rational process not dependent on subjective inputs coming from expert and users. Looking at the results, it can be seen how, through the analysis of the four groups of pillars and a few other inputs it is possible to obtain an update of an existing roadmap (ESA Space Exploration Technology Roadmaps) to sustain a particular mission of reference (i.e. HERACLES). A clear example of this is in the final choice of MCs to apply.

The applied methodology is an upgraded version of a previous version present in literature. Even if the upgrade is still valid in a reduction of the stakeholders' influence and in the automation of some decision making processes, the lack in modularity of the list of BBs leads to a decrease of generality and in a potential loss of possible connections between the pillars. In addition, sensitivity analyses and mode detailed decision making techniques will have to be employed to increase the rationality in the results.

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