Effective methodologies to derive strategic decisions from ESA technology roadmaps

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EFFECTIVE METHODOLOGIES TO DERIVE STRATEGIC DECISIONS FROM ESA TECHNOLOGY ROADMAPS

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Top priorities in future international space exploration missions regard the achievement of the necessary maturation of enabling technologies, thereby allowing Europe to play a role commensurate with its industrial, operational and scientific capabilities. As part of the actions derived from this commitment, ESA Technology Roadmaps for Exploration represent a powerful tool to prioritise R&D activities in technologies for space exploration and support the preparation of a consistent procurement plan for space exploration technologies in Europe. The roadmaps illustrate not only the technology procurement (to TRL-8) paths for specific missions envisaged in the present timeframe, but also the achievement for Europe of technological milestones enabling operational capabilities and building blocks, essential for current and future Exploration missions. Coordination of requirements and funding sources among all European stakeholders (ESA, EU, National, Industry) is one of the objectives of these roadmaps, that show also possible application of the technologies beyond space exploration, both at ESA and outside. The present paper describes the activity that supports the work on-going at ESA on the elaboration and update of these roadmaps and related tools, in order to criticise the followed approach and to suggest methodologies of assessment of the Roadmaps, and to derive strategic decision for the advancement of Space Exploration in Europe. After a review of Technology Areas, Missions/Programmes and related building blocks (architectures) and operational capabilities, technology applicability analyses are presented. The aim is to identify if a specific technology is required, applicable or potentially a demonstrator in the building blocks of the proposed mission concepts. In this way, for each technology it is possible to outline one or more specific plans to increase TRL up to the required level. In practice, this translates into two possible solutions: on the one hand, approved mission concepts will be complemented with the required technologies if the latter can be considered as applicable or demo; on the other, if they are neither applicable nor demo, new missions, i.e. technology demonstrators based on multidisciplinary grouping of key technologies, shall be evaluated, so as to proceed through incremental steps. Finally, techniques to determine priorities in technology procurement are identified, and methodologies to rank the required technologies are proposed. In addition, a tool that estimates the percentage of technologies required for the final destination that are implementable in each intermediate destination of the incremental approach is presented.

I. INTRODUCTION

The space sector is part of a complex and constantly changing world and an optimized planning of the resources and the projects is necessary to face with the various stakeholders' needs and to coordinate the top priorities, for example, in future international Space Exploration missions. In addition, to perform a roadmapping activity is important for many reasons. For example, globally and not only in the space sector, companies and agencies are facing many competitive problems: technology roadmapping is a form of technology planning that can help deal with this increasingly competitive environment, facing many parameters and situations at the same time and optimizing the final planning.

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 [1 2 3 4 5 6]. All present roadmaps are based on interviews with industries and experts and are generally manually updated every 2-4 years. 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 the variety of each single perspective that lacks 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 birth of ideas regarding new mission concepts.

Unlike [1 2 3 4], the paper does not focus on the results of space exploration roadmaps, but on the methodology developed to drive their 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 for human space exploration. In addition, 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 TRL or, more generally, to improve a particular kind of property in one or more elements between the one listed above. Indeed, Operational Capabilities (OC), Technology Areas (TA), Building Blocks (BB) and Mission Concepts (MC) are as a matter of fact the stepping stones of the methodology. Starting from any of these elements, the user can move through the other elements to assess his/her goal. For example, starting from a TA, the user proceeds with OCs, BBs and MC to eventually update the specific TA TRL. Moreover the methodology, here presented for space exploration purposes, has been developed for space exploration but cannot just be confined to space exploration, as it is suitable to address the creation of roadmaps of other fields of interest, like for instance aeronautics.

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 human space exploration scenario. 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 [9], BBs and eventually to technologies through a predetermined path. In addition, MCs has to be predetermined, whereas the present methodology aims at automatically generating new MCs, which may either be final operative missions or dedicated demonstrative missions. In addition, the methodology allows introducing constrains on OC, TA, BB and MC to opportunely cut off some unwanted results. Costs issues can be accounted as constraints. Costs are not considered in [7 8], where a technical approach is suggested.

Simultaneously, together with the methodologies to create roadmaps, in literature there are some tools that are intended as a way to track TRL evolutions and progresses and to acquire a global view. An example is TechPort [2]. TechPort is a public NASA tool, which is useful to locate information about NASA-funded technology development activities. In particular, this tool allows an external user to explore NASA's technology portfolio and learn about technology programs performed in NASA to increase technologies TRL in aeronautics, space exploration and scientific discovery missions. In addition, once technology investments are made, they are tracked and analysed in TechPort, which basically serves as NASA's integrated Agency technology data source and decision support tool. This kind of database enables NASA to compare the current portfolio with the Agency's priorities, providing results to NTEC and other decision bodies thus enabling an efficient management of the portfolio content.

The methodology that has been built for the technologies assessment is the main topic of this paper and a detailed discussion on it is reported in section 2. Furthermore, examples of how this methodology can be used are reported in section 3. Eventually main conclusions are drawn.

II. METHODOLOGY

The main objective of this analysis is to support the work on-going at ESA about the definition and the creation of technologies roadmaps. In order to better support this activity, the logical sequence of actions that has to be performed to create the roadmaps and the list of parameters and inputs that drive their creation have been studied. Consequently, an optimized methodology able to support the definition and the update of roadmaps has been defined. This methodology, applied at the right group of variables and inputs, is able to derive strategic decision for the advancement of Space Exploration. Four are the main elements involved in this methodology: Operational Capabilities, Technology Areas, Building Blocks and Mission Concepts.

First of all, an OC is defined as a high level function (i.e. an activity) responding to a mission statement [10 11 12 13]. A list of OCs has been derived, selecting areas of high importance that have an influence on the development of technologies. This list of capabilities has to be easily updatable and as general as possible. Indeed, a constant update has to be considered to take account of future innovations and new scientific frontiers. In addition, OCs has to maintain as general as possible perspective in order to be compliant with a higher number of applications. In particular, considering all these features, the selected OCs are: Rendezvous And Docking With (Non) Collaborative Target, 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]. OCs are part of the methodology and are strictly connected to the other elements.

The second element used in this methodology is the Technology Area (TA), considered as a set of particular technologies that accomplish one or more OCs. Also in this case, a list of TAs has been derived on the basis of ESA TAs, considering the main current and future research areas, and it has been quantified taking into account their Technology Readiness Level (TRL). Indeed, TAs are directly part of the process aimed at finding the best way to increase TRL: technologies evolve when they are subjected to experimentation, refinement, and increasingly validating tests. In this methodology, according to [1], the TAs considered 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. In addition, every TA is split into two supplementary sub-levels: “technology subject” and “technology”. The TRL update has to be performed at technology level.

A third element is the Building Block (BB). BBs are considered physical entities that may include several technologies combined together in different ways, achieving certain functions (OCs). The list of BBs, defined for the methodology proposed, exploits the concept of “modularity”, in order to generalize every BB to one or more specific elements. A significant modularity exploited is the concept of system, defined as an integration of different elements that together produce an effect not obtainable by the single elements, and sub-system, considered as a lower level element that with other sub-systems compose a more complex system. Applying these definitions, a single BB can be considered as a system and slit into the sub-systems that the system may need to accomplish its main goals (Fig. I). In this way, different applications and developments can be described: indeed, it is possible to be interested in developing a specific and simple BB (i.e. sub-system) or a more complex one (i.e. system). At system level the BBs considered are: Habitable Module, Transportation Module, Robotic Infrastructure, ISRU Infrastructure, and Satellite. In addition, every BB is described with a certain number of properties, representing the main performance required. Two main categories of properties have been defined: qualitative values (e.g. “Energy Source” property, defined as solar, fuel cells or batteries) and quantitative values (e.g. the range in kg/day of the “Leakage” property). The sub-system level for every system level BBs is composed by standard sub-systems (Fig. I). Due to this standardization, it is possible that a sub-system has similar name or properties list in different systems, but their properties are likely to be different, considering the different application of the top level BBs. Thanks to this eventuality, it will be possible to compare them and pile them up to create new missions or complement the existing ones. Every update in the BBs list or features may lead to modifications in the other elements, particularly in the TRL.

Finally, a fourth element considered is the Mission Concept (MC), which is defined with a mission statement and made up of BBs, implementing certain OCs and making use of certain technologies. In particular, in this methodology a MC can be defined as a union of BBs:

$$MC = \bigcup_{n=1}^{N} BB_n \qquad [1]$$

In order to define a list of MCs on which mapping the other elements, a categorization has to be applied, considering their advancement and funding. Particularly, MC can be defined as approved missions (i.e. missions described by a fixed and not modifiable list of BBs), missions under approval (i.e. missions where the BBs list can still be changed before being submitted to approval) and potential missions (i.e. likely missions that are under preliminary phase of conception). While the first category has been considered only in case certain technologies have low TRLs, the other two categories have been analysed in the present methodology. For the second category, a list of ESA mission proposals has been taken into account, identifying three target environments: Low Earth Orbit (LEO), Moon and Mars.

From the point of view of mission objectives, a further classification of missions is possible. Missions can

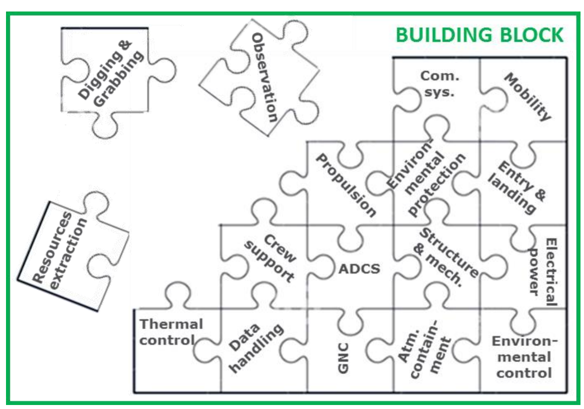

Fig. I: Building Blocks composition concept.

in fact be defined either as so-called operational missions (i.e. missions that have been planned to reach scientific and/or technological objectives) or so-called 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 missions can be defined totally operational or demo but most of the times missions can be defined part as operational and part as demo. In the latter case, it can be useful to express through percentage values how much of that mission can be accounted operational or demo. This classification can apply to all categories of missions, i.e. approved missions, missions under approval and potential missions, previously identified. It is worth noting that the presence of these “demo” MC will be very useful for the TRL increase estimation.

In addition to the categorization of missions mentioned before, missions can generally be subdivided also according to the environment in which they will operate. Thinking of space exploration, four main environments can be observed: Earth, LEO, Moon and Mars. LEO, Moon and Mars apply to both operational and demo missions, as well as to approved missions, missions under approval and potential missions. Conversely, Earth environment does not apply to final operational missions, as it has been introduced specifically for demo missions. In fact, as far as demo missions are concerned, Earth environment may include missions or generally activities (i.e. testing activities) that, starting from theoretical researches proceeds with laboratory components/breadboard validation activities (i.e. lower TRL), and eventually ends up with missions of components/breadboard validation in not controlled environment and missions of system/subsystem prototype demonstration in not controlled environment (i.e. higher TRL). In the TRL increase estimation, these specific MCs will be evaluated separately from the other, considering also the different level of resources that they require. Taking again specifically into account demo missions, we can say that LEO environment can include components/breadboard validation missions and system/subsystem prototype demonstration missions. An example of this particular kind of MC is the IXV (Intermediate eXperimental Vehicle, the ESA Re-entry Demonstrator) mission, flown in February 2015 [14].

Every MC in the defined list has to be attached to properties in order to describe its features. Examples of properties can be MC timing (i.e. launch date, starting and ending time) and financial resources (i.e. resources amount and kind of fund used). In addition, the list of MCs and their properties need a continuous update, in order to take into account not only future market developments or technological achievements, but also better drive and sustain resources optimization.

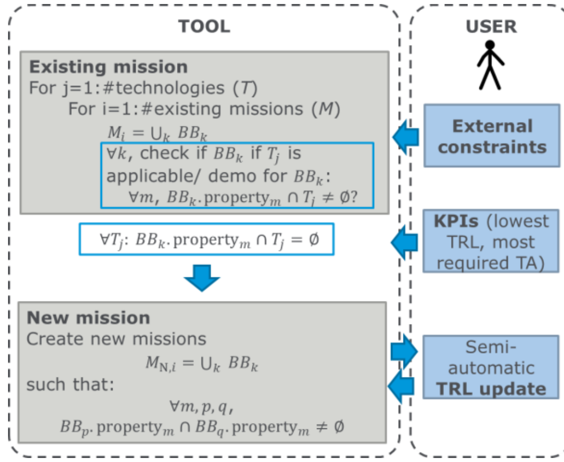

Fig. II: Algorithm for MCs application or generation.

In addition to the list of MCs identified, an algorithm to suggest new MCs has been introduced. This algorithm may be applied to define the MCs properties and the involved BBs for those MCs before categorized as potential missions (both operational or demo missions). This feature is particularly important when, at the end of the analysis, no existing MC is available to increase the TRL up to a desired level: one or more MCs can then be suggested from the methodology to the user, specifying their properties and BBs composition and taking into account the imposed constraints. Through this algorithm is therefore possible to plan new MCs (Fig. II). Indeed, if all MC features and the type of the BBs required are known, a new MC can be suggested automatically. To this purpose, Key Performance Indicator, KPIs, have to be introduced to prune the number of combinations that this algorithm may create. 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 resulting in feasible MCs. Some pruning criteria have therefore to be introduced and have to be specified by the user, in order to reduce this number of MCs and select an optimal output.

As for the other elements here described, the main goals of MC definition are TRL increase and capabili-

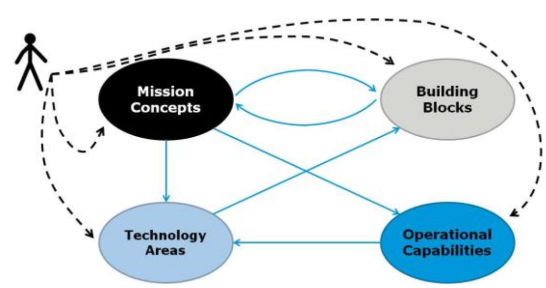

Fig. III: Possible path among the main elements: MC, BB, TA and OC.

ties 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. III). Indeed, the main aim of the proposed methodology is to derive strategic decisions for future investments in TAs, regarding both their development and their demonstration to enable operational OCs. As Fig. III 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 TA, to move then to the required BBs and eventually to MCs, defining also the OCs that are involved in the TRL increase. This flexibility of the tool is an important feature, being necessary to customize the technology roadmaps to the user needs. One of the fundamental tools used in this methodology to link every element, describing the strict correlation between them, is the applicability analysis. The main purpose of this tool is to detect if a specific element is required, applicable or potentially a demonstrator in the other elements.

Applicability analysis is intended as the analysis performed to map one element of the methodology onto the others. In particular, four types of applicability analyses have been considered: applicability of OCs onto TAs, applicability of TAs onto BBs, applicability of MCs onto BBs, and applicability of technologies onto technologies (see Fig. IV and Fig. V). In these applicability analyses, the relationship between two elements is described by four labels: required (i.e. highly impacting relationship), applicable (i.e. relevant but not strictly needed relationship), demo (i.e. combination never applied before and considered in a mission planned specifically for validation purposes, i.e. a demo mission) and test (i.e. combination never applied before and considered in a mission planned not specifically for valida-

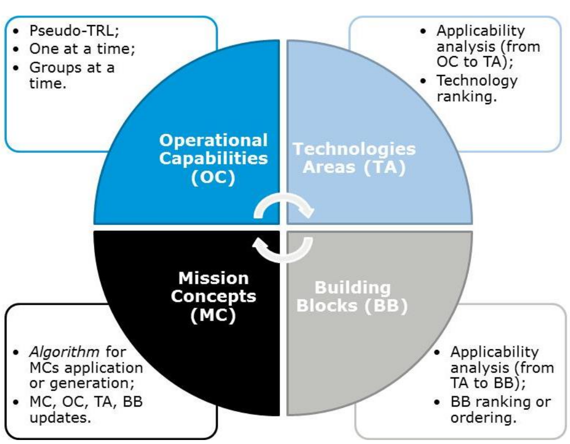

Fig. IV: Methodology for TRL increase through OCs, TAs, BBs and MCs.

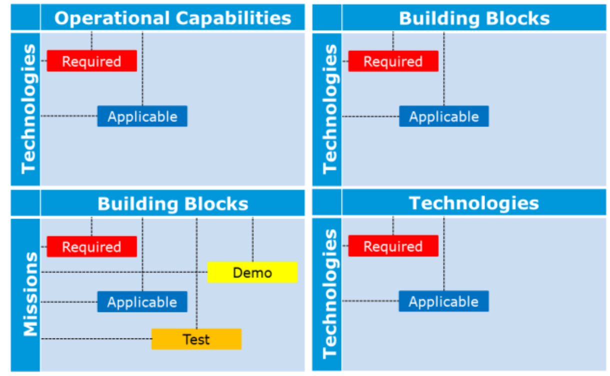

Fig. V: Applicability analyses.

tion purposes, i.e. operational mission). The last two labels are introduced with the purpose of driving the TRL update process, because they are related to time. In addition, only in the MCs onto BBs applicability analysis is possible to introduce these labels, as reference to the time frame arises only in the MCs onto BBs applicability analysis. It is worth mentioning that in case each single mission could be expressed through percentage values as partially demo or operational, there would be no need for the label "test", which actually applies to missions that are, for instance, mostly operational but partially demo. Another important applicability analysis for the TRL update evaluation is the last applicability analysis (i.e. technologies onto technologies). Indeed, this analysis allows understanding which technologies can be tested together, maybe in the same mission either as test or as demo BB. 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.

The applicability analyses give therefore information about possible relationships between the elements of the methodology but further methods have been introduced in order to rank technologies and build new missions. The rationale behind it is that the intention to improve one or more TAs will drive the identification of the most suitable BBs and eventually MCs, which, combined together will succeed in achieving the established goals (Fig. IV). As far as technology ranking is concerned, important data for technology prioritization are provided by the applicability analysis between TAs and BBs. Indeed, two criteria can be considered to rank technologies: "most required" (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 (and required) technologies. Technology ranking is fundamental when the user has to deal with many technologies, as for instance in case the user is interested in enhancing one OC, which can be linked to various TAs. Conversely, in case the user is interested in increasing the TRL of one single technology, apparently no technology ranking is necessary. However it is important to look at the road-mapping activity as a whole, thus inserting that selected technology in a complete roadmap.

Once the technologies have been ranked, it is important to find a way to re-order and prune the list of the BBs before they are applied to MCs. With this purpose, constraints may be introduced over BBs, over BBs' properties, over MCs or over MCs properties. The capability to introduce constraints is important because gives the opportunity to the user to drive the analysis and customize and optimize the results. As already mentioned, constraints can be applied to all elements or to their properties. For example, for each constraint C_i applied to a generic MC property (e.g. $C_i \neq "Mars"$), the following expression must be true for a mission MC_j to qualify the user input:

$$MC_j \cap C_i \neq \varnothing \qquad [2]$$

Specifically, through the applicability analysis between MCs and BBs is possible to associate a list of MCs to the already found list of BBs, thus identifying the total number of MCs available for a specific BB. At this point, it is possible to distribute the available MCs (i.e. the resources) on the specific BB's technologies. This particular step of the methodology has to be referred to the technologies prioritization, in order to distribute the resources in an optimized way, giving more importance to those technologies that have a higher ranking. In particular, a criterion to perform the ranking between BBs and MCs has been introduced. This particular criterion has been applied in order to assign a number of MC (S_p) to a technology ranked p, if it is considered a specific BB with m total MCs and n total technologies:

$$S_P = \frac{n-p+1}{a_n} \cdot m \text{, with } n \geq 1 \text{ and } a_n = \frac{n(n+1)}{2} \qquad [3]$$

This ranking has to be performed considering not only the BBs and MC properties, but also the technologies that are applicable or required to every MC-BB combination. Technologies can be considered using as constraints the applicability analysis of technologies onto technologies, which help understand whether or not the technologies that are already integrated in every MC-BB can be combined with new selected technologies. If the new selected technologies can be coupled to those already integrated, they can be considered applicable/required/demo/test in the MC under analysis. On the contrary, in case two or more technologies cannot be integrated in the same BB, the total number of MCs for the technology with a lower rank in the technologies prioritization will be constrained by the available number of MCs for the technologies with higher rank.

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 have been introduced is called pseudo-TRL. This parameter is based on the concept that for every OC, knowing the technologies that are mapped over it, the TRL values of those technologies can be used to define the current state of the capability. Pseudo-TRL can be obtained as follows for each OC A, linked to a required technology i (considered with a weight of r_i) and to an applicable technology j (considered with a weight of a_i):

$$pseudo-TRL_A = \frac{TRL_i + TRL_j}{r_i + a_j} \text{ where } r_i \geq a_j \qquad [4]$$

Particularly, the values used are: 1.5 for r_i and 1 for a_j. This implies that the smaller is the pseudo-TRL the higher is the priority with which that OC will be addressed among others (if considered).

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.

As far as the estimation of the time necessary to improve TRL, it is worth noticing that all mission categories have to be analysed. Indeed, while data about time are fixed and known in approved missions, when it comes to potential missions a value for the ending mission time has to be suggested. In addition, not all the MCs listed at the end of the methodology will be chosen by the user for the TRL update. Supposing to have a fixed list of MCs and that all the missions in this list are used for the TRL update, supposing to have all the ending times of these missions, it is then possible to combine these missions and their properties to the technology TRLs, thus generating a feasible incremental path,

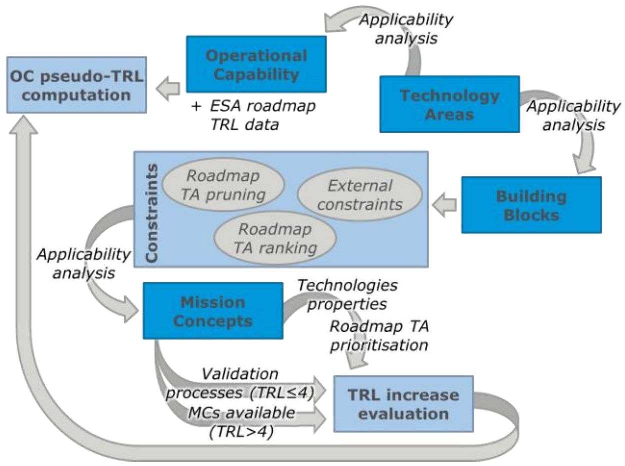

Fig. VI: Detail of the methodology proposed.

in case a step by step approach for the TRL increase is assumed.

III. RESULTS

To support the work on-going at ESA about the roadmapping activity promoted on Exploration Technologies, in order to coordinate ESA Directorates and European Industry, a study has been performed about the logical sequence of actions that has to be performed to create technology roadmaps and the list of parameters and inputs that drive their creation. Consequently, an optimized methodology has been proposed, with the main purpose of developing technology roadmaps' assessment, in order to derive strategic decisions for the advancement of Space Exploration. In particular, applying this methodology, a set of suggestions about possible MCs and resulting TRLs increase are derived from four selected categories of elements. This section explores how to use this methodology for roadmaps generation, highlighting its flexibility and the effectiveness of its results. A case study is here proposed to show the methodology capability.

The analysed example concerns the evaluation of the process needed to increase the TRL in the Inflatable Technology for Surface Application: "Lightweight habitat structures with views, Deployable and Inflatable Structures" technology. This specific technology addresses sub-element demonstrators (to be tested also on ground and in-orbit), feedthroughs and secondary components for deployable/inflatable structures outfitting, inflatable and soft racks. In Europe, currently, this technology is funded with resources available for inflatable structures in the frame of the STEPS2 program [15].

As already mentioned, in order to analyse Inflatable Technology for Surface Application, "Lightweight habitat structures with views, Deployable and Inflatable Structures" has been considered. In particular this technology is part of a wider TA, "Advanced Structures & Mechanisms Applications" and the technology subject "Structures for Surface Applications" [1]. The current TRL for our technology is 5, which according to literature definitions [10], means the test of component and/or breadboard validation in relevant environment. Considering a technology and all its features (e.g. the testing environments or the possibility to use it in BBs or in MCs) necessarily implies a higher accuracy, but at the same time it turns out to be more time consuming and more demanding in terms of specific knowledge, thus requiring the support of specific disciplines experts.

In the proposed example, we consider as starting point a user that is interested in enhancing the TRL of this technology. A plan for the development of this technology is then proposed, involving all the capabilities, the building blocks and the missions connected to the chosen technology. At the end of this analysis, an update of the elements involved and their properties has to be performed. Considering Fig. IV, once the TA (and TRLs) has been clearly identified till the technology level, it is mapped onto BBs. Consequently, BBs are searched among the existing missions: if correspondences are found, then applicability of these BBs to missions is suggested. A detailed scheme of the methodology applied to the specific case-study is shown in Fig. VI.

After technologies over OCs applicability analysis, a list of technologies applicable to Inflatable for surface application technology, a list of applicable/required OCs has been derived. Data about all the roadmap technologies current TRLs are available [1] and the current pseudo-TRL for all the OCs is obtained through [4] (Fig. VII).

Another applicability analysis that can be performed is the one between technologies and BBs. This analysis leads to the identification of Habitable Module and ISRU Infrastructure BBs as applicable/required. In particular some subsystems of these macro-BBs have been considered as related to our technology. For now, properties of these BBs are not considered, but at some point properties may need to be specified, because it might happen that some properties clash with some of the constraints imposed on mission application or generation.

Finally, having defined the available BBs, a third applicability analysis of BBs onto MCs allows the definition of the available MCs. Due to the great number of MCs, some constraints are applied to prune the results, and eventually discuss the outcome of the work. In particular, two constraints are introduced: MCs have to be manned and only habitable modules are allowed. The first constraint applies to mission type and can be transferred at BB level so as to take into account those missions where BBs "Environmental control system" and "Crew support system" are at least applicable. On the contrary, the second constraint arises from several con-

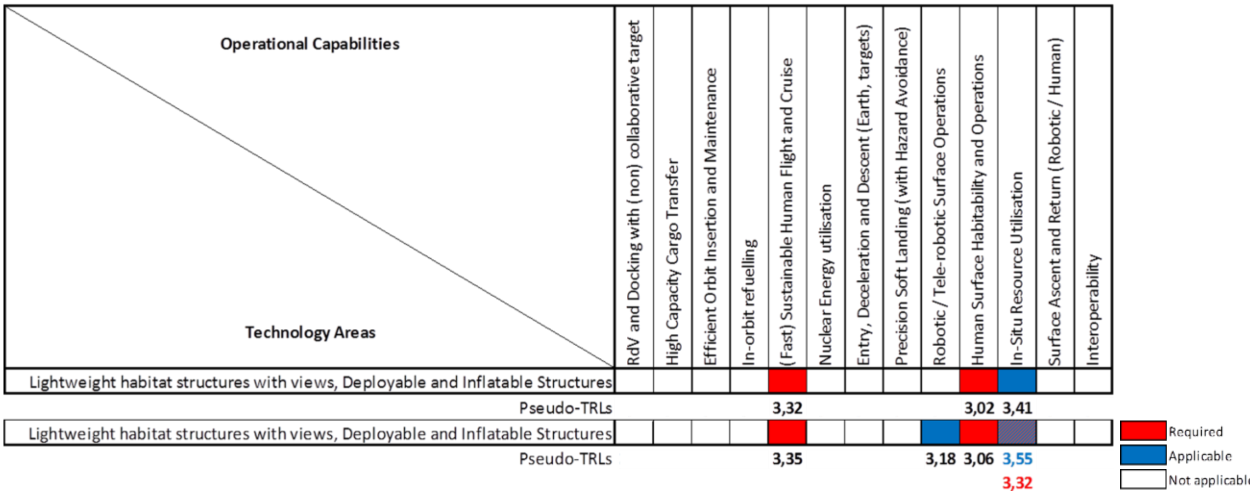

Fig. VII: Applicability analysis (TA/OC) for the inflatable technology development with constraints, where changes and pseudo-TRLs are shown.

straints on BBs properties that do no match ISRU infrastructure properties. In addition, this constraint might be on ranges that are not met by some of the BBs properties. For example, in “ISRU infrastructure” / “Environmental Protection System” BBs the following properties can be involved: Radiation levels Micro Meteoroids and Debris Protection material, Micro Meteoroids and Debris Protection width, Heat leak is limited, Insulation material/system.

As a result, after the application of the constraints, only some MCs and BBs can be retained. It has to be said that all the dedicated demo missions are still considered. This is due to the definition of the demo label and the consideration that, if a demo mission is created deliberately for a specific technology demonstration, it will be certainty compliant with the constraints.

Some additional data have to be considered as constraints. Indeed, in addition to the external constraints, some additional constraints may arise from the roadmap itself. Indeed, even if in this particular example only one technology is considered and all the ranking and prioritization logics between technologies are not introduced, in a wider scenario, this particular technology TRL increase has to be studied considering all the other technologies and the priority assigned to them. This kind of constraints is particularly important in associating the analysed technology to the list of MCs found. Indeed, when missions are already approved, these MCs can be created around a group of technologies that can be conflicting with the one under study. On the contrary, when a potential mission is considered, different technologies can be introduced by other user in other kind of analysis. In addition, also the actual TRL of the inflatable for surface application technology has to be considered. This last information will prune the MCs list, in particular in the number of demo missions: being the actual TRL at 5, the demo missions specifically dedicated to the TRL increase at lower levels are not necessary.

As predicted, after the application of the constraints, the number of proposed missions (Fig. VIII) has to be updated, together with the mapping of TAs onto BBs and the one between TAs and OCs. In addition, a pseudo-TRL recalculation is required and will only be affected by TRL increase of inflatable technology for surface applications.

Considering all the OCs that are applicable or required for the analysed technology, an attempt to evaluate their pseudo-TRL has been performed before and after the application of our methodology. Indeed, every update in the features of the selected technology will affect the applicability analysis between OCs and TAs, as already explained: considering these changes, different pseudo-TRLs can be reached for every OCs where the considered technology is shown as applicable or required (Fig. VII).

In order to update 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. Firstly, it is important to assign different weights to the list of MCs obtained, considering the different level of resources that the MCs can require. Indeed, MCs that help achieve a TRL lower than 4 may need fewer resources and generally all these MCs can be used when required for TRL increase. On the contrary, MCs that help achieve a TRL higher than 4 may show difficulties in their actuation for the necessary involvement of more resources and generally not all the MCs listed are required or available for the TRL increase. While the first group of MCs is not required (the actual TRL is 5), the remaining ones can be considered as applicable over the BBs. Considering the actual list of MCs and the actual TRL, not all the MCs are required for the TRL increase. Indeed, looking at Fig. VIII, two demo missions are available for the TRL increase up to 6, and one of them has to be excluded (probably the one in LEO environment for the higher level of resources involved). In addition, it is worth remembering that every BB has to be considered singularly and that the one with the least number of available MCs has to be considered as the constraining condition. Many other inputs are required for the TRL increase estimation, not only the number of MCs that are applicable of required in this analysis or the actual TRL of the considered technology. For example, Technologies over 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. Assuming that no criticalities have arisen, the final list of MCs applicable or required to the selected technology is the previous one. Otherwise, the TA with the highest priority has to be considered first allocating all demo and operational missions that this TA can perform in order to increase its TRL. Then the remaining missions can be used for the TA with lower priority. Finally, using all this information, an attempt to estimate the possibility of reaching TRL 9 has been performed (Fig. VIII). Both approved and potential missions have to be analysed. Ending times are known for approved missions: in this example ExoMars 2016 and 2018 will end respectively in 2021 and 2018 [1]. On the contrary, the ending times of potential missions have to be estimated. In case of final operational missions, an average value of 10 years has been fixed for the preparatory phase. To this particular time has to be added the transfer time between the two environments and back. The environments considered are Moon and Mars. The transfer time between Earth and Mars, considering the synodic time and Hohmann transfers is about 4 years [16], reaching a total duration of 14 years. On the contrary, in trans-lunar injection the transfer time between Earth and Moon (and back) is of about some days: considering an operative phase this time has been increase to one year. Consequently, the total time considered for Moon MCs is 11 years. It has to be said that the preparatory phase of a MC can be performed before the end of the subsequent MC. Finally, it is supposed to use two demo mission to reach TRL 7 (one in Earth and the other in LEO environment) in 7 years, using as reference the IXV mission [14]. In addition, one MC in Moon environment is assumed to reach TRL 8 (i.e. LEO Exploitation - permanent station) and is possible to reach

	Building Blocks / Mission Concepts	Hab. Mod.: Atmosphere containment system	Hab. Mod.: Environmental protection	Hab. Mod.: Structure & mechanisms	ISRU in.: Environmental protection	ISRU in.: Structure & mechanisms
Earth	*Theoretical principles formulation*	2	2	2	2	2
Earth	*Analytical proof*	3	3	3	3	3
Earth	*Experimental proof*	3	3	3	3	3
Earth	*Laboratory components/breadboard validation*	4	4	4	4	4
Earth	*Components/breadboard valid. in not controlled environ.*	5	5	5	5	5
Earth	*Sys./subs. prototype demo. in not controlled environ.*	6	6	6	6	6
LEO	*Components/breadboard validation*	5	5	5	5	5
LEO	*System/subsystem prototype demonstration*	6	6	6	6	6
LEO	*Complete system flight qualification*	7	7	7		
LEO	LEO Exploitation - permanent station (ISS, post-ISS Station)	8	8	8		
LEO	1st MPCV Unmanned Demonstration Mission					
LEO	2nd Manned MPCV Manned Demonstration Mission					
LEO	LEO Exploitation - Free flyers (e.g. Dragon, Dreamchaser)					
LEO	Follow-on MPCV Missions					
Moon	Luna-Resours-Lander					
Moon	Lunar Polar Sample Return					
Moon	Extended crew duration missions in cis-lunar space					
Moon	Human-lunar surface missions	9	9	9		
Moon	Human-robotic Partnership Missions					
Moon	*Human Assisted Sample Return*					
Mars	ExoMars 2016					
Mars	ExoMars 2018					
Mars	Post ExoMars mission					
Mars	MSR preparation / MSR elements					
Mars	Enabling long term technology					
Mars	*Human Mars*					

Fig. VIII: MCs applicability for inflatable technology development applying the constraints, the MC supposed for TRL increase are highlighted.

TRL 9 in "Lightweight habitat structures with views, Deployable and Inflatable Structures" considering one mission in Moon environment (i.e. Human-lunar surface missions). Considering other 7 years to perform the third mission and assuming to perform it during the preparatory phase of the fourth mission (as for the other demo missions), it is possible to reach TRL 9 in about 15 years considering all the preparatory phases and the timing for approval.

IV. CONCLUSIONS

The main purpose of this paper is to describe the methodology developed in support to the work on-going at ESA about the definition and the creation of technologies roadmaps on Space Exploration, coordinating technological and financial resources among different projects. Eventually the main methodology capabilities are shown in a case study. In order to better support this activity, the logical sequence of actions that has to be performed to create the roadmaps and the list of parameters and inputs that drive their creation have been studied. Consequently, an optimized methodology able to support the definition and the update of roadmaps has been defined. Four are the main elements involved in this methodology: Operational Capabilities, Technology Areas, Building Blocks and Mission Concepts. The main objective of the here presented methodology is to derive strategic decisions for future investments in TAs, regarding both their development and their demonstration to enable OCs.

Particularly, the main logic under the methodology here proposed is to create MCs, by the aggregation of BBs for technology and capability demonstration, optimizing their creation. Indeed, it is necessary to minimize the number of required MCs for an optimal resources repartition, while all the required TAs are considered together. The proposed methodology is able to suggest a possible path for TRL increase, or at least to drive a hypothetical user in an optimized path for TRL increase, taking into account other users' needs, constraints from resources availability and timing. Indeed, semi-automatic suggestions for each technology TRL update can be explored, considering both time and final level achievable. Within this framework the connection between MC environments (ad test and demo missions) and properties (as starting and ending times) and the TRL definitions has been considered.

In this context is surely important to consider feedbacks from experts or inputs from the users: these feedbacks are useful not only to optimize the results, but also to correctly update the roadmaps in case new simulations have to be run. In addition, this particular feature makes the created methodology able to be flexible enough to be addressable to the widest possible range of users. The methodology flexibility is in the many possible paths that can be exploited between an element and the other. This particular feature makes the methodology adaptable not only to an expert user, but also to less specialized ones. In addition, the methodology flexibility is required to make it easily updatable: frequent updates will be required not only in the basic elements lists but also in their features and in the applicability analysis to meet and modernize Space Exploration goals. For example, in updating the applicability analysis, one or more demo (or test) technologies may become applicable, some applicable technologies may become required, and new connections between elements may arise.

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