Technology RoadmappIng Strategy, TRIS: Methodology and tool for technology roadmaps for hypersonic and re-entry space transportation systems

Technology RoadmappIng Strategy, TRIS: methodology and tool for Technology Roadmaps for hypersonic and re-entry space transportation systems

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This paper describes the methodology developed by Politecnico di Torino in support to the elaboration of hypersonic and re-entry space transportation systems roadmaps, currently on going at ESA. TRIS (Technology RoadmappIng Strategy) is here presented as a collection of algorithms leading the stakeholders from the selection of a set of elements (e.g. the technologies) up to the generation of their incremental paths towards a final target (e.g. Technology Readiness Level (TRL) 8). In particular this paper focuses on the generation and update of technology roadmaps for hypersonic and re-entry systems. In particular, the Intermediate eXperimental Vehicle (IXV) experiment is presented as validation case study, allowing the comparison of the TRL increase path suggested by the proposed methodology and the decisions that were taken at the time of the IXV mission planning.

I. Introduction

In the last decades, an increased competition has brought technology and innovation management to the centre of decision-making processes aimed at understanding the relationships between technological capabilities or current technological expertise and objectives to reach. In this context, it appears clear that decisions not including technological considerations for the development of innovative solutions are unsustainable in a fickle and competitive market. A useful tool to monitor the current technological state and the plans for its future advancement is a technology roadmap.

The first roadmapping activity was carried out by Motorola to improve the alignment between technology and innovation [1] in 1987 and its application has become increasingly popular during the last decades, being adopted by many companies, governments and other institutions around the world [2][3][4]. A technology roadmap is the output of the technology roadmapping process, a set of activities aimed at identifying and selecting technologies, mission concepts, capabilities and building blocks according to specific strategic plans. Starting from the definition of a set of targets to reach, the roadmapping process identifies the critical system requirements, the product and process performance targets, the technology alternatives and the milestones [5]. A roadmapping activity is a complex and continuously evolving process that involves many parameters at the same time. For example, a technology roadmap definition process has to relate with current or changing limitation of financial resources by both the government and industry, with scientific or technical needs and with current general public requests.

The paper presents the results of a research activity carried out by Politecnico di Torino in support to the work on-going at ESA on the generation of technology roadmaps for hypersonic and re-entry space transportation systems. The research question is how technology roadmaps can be generated in a structured way. The approaches reported in literature and currently used in several industrial contexts are based on workshops, brainstorming, meetings, etc. Consequently, roadmaps generated in this way are strongly related to the specific stakeholders involved into the process. The idea of Politecnico di Torino is to develop a rational and objective methodology to generate technology roadmaps to better support strategic decisions in combination with traditional methods. The new methodology shall support traditional approaches providing a higher level of abstraction, showing up a multiplicity of possible incremental paths towards the final goal.

In particular, this research activity foresees the development of a logical methodology based on the combination of common System Engineering tools and processes [6][7][8][9] with ad-hoc developed tools and called Technology RoadmappIng Strategy (TRIS). Thanks to different case studies based on ESA Space Exploration Technology Roadmaps [2][10], TRIS is currently able to derive, track and manage basic space exploration roadmap elements [11][12][13] and to optimize their relationship in a decision-making process [14][15][16]. The results achieved allow TRIS to be suitable for a similar roadmapping exercise to be performed in the field of hypersonic and re-entry space transportation systems, to support ESA's technology inititatives within this field, as demonstrated in previous publications [17][18][19][20].

Undeniably, even if Europe has access to space, it has a limited experience associated with hypersonic, (re-)entry and landing vehicles on Earth and other celestial bodies with an atmosphere. Nevertheless, in 1998 ESA has flown Atmospheric Re-entry Demonstrator (ARD), an Apollo-like capsule that performed a suborbital re-entry path, as part of the run-down Manned Space Transportation Program (MSTP) ,which marked the end of the Hermes related work [21]. More recently with the German Phoenix [22] and the italian Unmanned Space Vehicles (USV)[23][24], Europe has performed some flight experiments related to the mastering of winged space vehicles' Guidance, Navigation and Control (GNC) during the landing phase. Furthermore, with the German Sharp Edge Flight Experiment (SHEFEX) [25] Europe has been investigating the potential of very high lift over drag configurations for space vehicles, based on a sharp edged faceted concept. Finally, it has to be mentioned the Intermediate eXperimental Vehicle (IXV) experiment [26][27][28], that performed a successful Earth-atmosphere re-entry flight experiment following a sub-orbital flight path. Despite these efforts, the need of plans also for Europe to increase its presence in the market related to the field of hypersonic and re-entry space transportation systems has become even more compelling, in these last years. Indeed, in the past few years, commercial private initiatives (in particular in the USA) have developed and commercialized vehicles capable of missions including Earth re-entry and, eventually, partial re-usability of vehicle elements [29].

After this introduction, before describing the methodology developed at Politecnico di Torino to drive the generation and update of technology roadmaps, Section II is collecting the most interesting initiatives in the field of roadmapping activities, identifying pros and cons of each method. Then Section III describes in details the methodology developed to generate roadmaps of hypersonic and re-entry systems. Furthermore, to provide evidence of the methodology, the overall process has been applied to a specific case-study: the IXV experiment. Then, the results of the methodology are presented and compared with the decisions taken at the time of IXV. Eventually, main conclusions are drawn together with the identification of improvements to the methodology as well as the identification of other test cases and fields of application.

II. Overview of roadmapping strategies

Before developing a new methodology, it is absolutely important to monitor the status of the art of currently adopted methodologies. Based on [30] , six types of procedural roadmapping methodologies can be identified:

1. *Fast-Start Technology Roadmapping*, based on workshops aimed at supporting innovation and strategies suitable for roadmapping activities at product and business level;
2. *Technology-Driven View Technology Roadmapping*, based on a technology-driven approach that refers to the actual technological evolutionary trend aligning technologies with business strategies;
3. *Market-Driven View Technology Roadmapping*, based on a market-driven approach that refers to the actual technological evolutionary trend and the modelling of the environmental scenarios;
4. *TRIZ-based Technology Roadmapping*, where TRIZ stands for Teoriya Resheniya Izobreatatelskikh Zadatch or Theory of the Resolution of Invention-Related Tasks;
5. *Delphi-based Technology Roadmapping*, based on a Delphi process, decision technique applied in state agencies to support independent stakeholders in making decisions through rounds of interviews;
6. *Innovation Support Technology (IST) Roadmapping*, based on a business-oriented process for normative-based technology roadmapping, starting from a preferable future scenario.

It can be seen that some of these methods aim at satisfying technologies' requirements while other seem to be pushed by market or business-oriented requirements. Technology-driven approaches are applied when it is necessary to explore the different opportunities before identifying the future scenario, while market-driven approaches help to ensure that appropriate technological capability is available according to stakeholders' strategies [30]. In the example of a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme, a method that takes into account both approaches can be preferable. Indeed, while it is important to consider market and business strategies coming from different and multiple stakeholders, it remains important to explore different future scenarios without proposing a precise path to be followed. It is fundamental also considering that it can be very difficult to define at the beginning of the process a future scenario able to please every stakeholder. An example of pure "Technology-Driven View Technology Roadmapping" is the one proposed by Schuh [31],[32] and also known as Technological Overall Concepts for Future-Oriented Roadmapping. According to them, it is different if the roadmapping activity is based on the definition of sector-wide technological overall concepts (i.e. roadmaps based on megaprojects) or on enterprise-specific technological overall concepts (i.e. roadmaps based on individual enterprises). In this case, the proposed roadmapping process is based on plenary councils, consortiums and integration teams to review strategic options, priorities and objectives. In particular, the process has to start with the definition of the objectives and the elements (i.e. the technologies) that compose the specific concept. The concept has to be detailed and then communicated and applied. On the contrary, an example of pure "Market-Driven View Technology Roadmapping" is the one proposed by Geschka [33],[34] and also known as Scenario-Based Exploratory Technology Roadmaps. The peculiarity of this process is in the additional analysis of non-technical requirements, such as related to societal and economic factors. Based on these factors, different scenarios have to be formulated and studied to define how to achieve a preferred future technological situation. Unfortunately, even if scenario-based technology roadmaps are an instrument of technological forecasting, they are not a planning instrument [30]. In both the examples, experts' opinion remains the main driver and a limitation is in the lack of tools or algorithms able to support and simplify the roadmapping activity if applied to complex system or to a System of Systems (SoS) design. In addition, they require specific knowledge of the involved technologies or scenarios. This knowledge may not be available at early design stages when dealing with a SoS design due to the different number of programmatic and technical requirements to be taken into account.

In literature, many methods deal with workshops and working groups of experts able to define roadmaps thanks to their interaction. An example is the one proposed, in [30],[35],[36], the "Fast-Start roadmapping workshop approaches". This approach guarantees differerent points of view: a technology-driven method also known as "T-Plan" (i.e. based on product-technology roadmapping) and a market-driven method also known as "S-Plan" (i.e. based on general strategic challenges at business, corporate, sector and policy levels). The main peculiarity of the these methods is that they are based on interactive workshops between different groups of stakeholders. Another example is the "Delphi-based Technology Roadmapping" proposed by Kanama [37],[38],[39]. Exploiting the Delphi method, even if in an hybrid version that allows technology roadmapping as the result of the process, means to exploit panel visions and roadmapping working groups to define sub-roadmap to be integrated in the final roadmap. Finally, another example of method highly related to interaction with experts, is the "IST Technology Roadmapping" proposed by Abe [40], [41] . Even if this method is supported by Decision Analysis tools (such as the strategy grid), it is still based on different workshops able to drive the technology roadmapping process. Even if the basic assumptions of this approaches remain true, a roadmapping activity in the context of an ongoing large-scale collaborative programme has to be performed at the beginning of SoS design activity, phase in which not all the data are available and that usually deals directly with stakeholders' ideas. This may lead to not structured inputs and may reduce the final planning effectiveness. Another limit is in the possibility of a high influence of personal and political interests that limit the capability of the process.

Both the difficulties in defining specific knowledge of the involved technologies or scenarios and in considering stakeholders (or experts) inputs in early design phases' roadmapping activities can be overcome with modelling and simulation techniques, with the drawback of increasing significantly complexity and, therefore, the time to achieve expected results. On the contrary, there are many methods based on innovation and procedure to track and manage innovations. An example is the "TRIZ-based Technology Roadmapping" proposed in [42]. TRIZ [30],[35] is a particular forecasting tool based on a technology-driven approach to study future technological innovations. Even if this method is a structured process for technology-driven roadmapping, it is incomplete for mission-oriented case studies. In addition, even if TRIZ is supported by a tool, it requires specialized knowledge of the analysed problem in order to decompose it into smaller standard. However, TRIZ remains a significant support to define future innovations trends of technologies at the highest maturity level starting from current market strategies.

Some other technology-driven methodologies are available in literature, dealing with a mission-oriented approach. An example of Mission-Oriented Technology Roadmapping is the one proposed by Viscio [43]. The methodology is able to define where, how and when a set of technologies will achieve maturity according to a reference human space exploration scenario and on the basis of a defined database [44],[45],[46]. Unfortunately, this method has a limited flexibility in application field, even if it can be extended to various reference missions in the same field. In addition, it is difficult to be supported by a database containing the required basic data for a roadmapping process. It has to be said that in literature some examples of databases exists, also giving the possibility to track technology maturity evolutions and progresses and to acquire a global view. Examples are TechPort [47], a public NASA tool, and TREx [48], a tool developed by ESA. Both of them allow the location of data about technologies, programmes and technology maturation activities funded by the space agency of reference. Due to the possibility to track current investments, these tools are a support for decision-making activities. In addition, in [43] only a technical approach is proposed, not considering programmatic requirements (e.g. costs and schedule). These types of requirements are important to be considered in a roadmapping activity to integrate inputs coming both from technologies and from business processes. The European Industrial Research Management Association (EIRMA) [49] has proposed a similar view, later-on adopted by the major space agencies for its ability to relate directly business processes, programmes, strategies, systems and technologies to a time perspective.

As said before, considering the example of a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme, a method has to be defined able to deal with the specific features of the context under analysis and has to be optimized for it in order to guarantee rational results. In addition, in a similar context a reduced number of workshops and interactions with the stakeholders can ease the roadmapping process, being the stakeholders in a significant number and from different realities with different strategies and policies. The roadmapping approach has to consider all these limitations and all the specific context features, but it remains true that what is present in literature is the state of the art for this type processes and has to be considered as reference. For example, it is true that EIRMA point of view is a good solution for roadmaps where design processes are taken into account, but alternative methods have to be applied to define many roadmap data and to propose eventual links between them to evaluate a planning that involves them. A significant support in the roadmapping process can be in the analysis of the relationships with the System Design Processes. Indeed, exploiting System Design Processes tools and theories in the roadmapping approach, it is possible to simplify also the roadmapping process itself, generating rational draft result to be reviewed or easing the update process because these tools are based on modular and structured pillars (i.e. roadmap elements) directly related with their design process. This is particularly true in this context. In particular, a methodology will be proposed in the next section able to generate and update roadmaps on the basis of a typical Systems Engineering Conceptual Design approach [50] and exploiting an iterative and recursive multi-steps procedure that is based on NASA and ESA guidelines for the design of complex systems [51],[52].

As a result, taking inspiration from all these processes and remembering the main purposes of this research activity, a methodology for technology roadmap definition and update will be proposed in the following section. In particular, it has to be remembered that the main objective of this research are:

− To analyse SoSs knowing the scenario of application and a few programmatic requirements coming from stakeholders;

− To propose a draft roadmap to stakeholders and experts for review, simplifying and speeding up the roadmapping activity;

− To at least partially automatize the roadmapping process.

For these reasons, it is necessary to deal with mission-oriented approaches (first point in the previous list), to deal with data-based approaches rather than experts-based ones (second point) and to normative methods rather than explorative ones (third point). The application of a mission-oriented point of view imply a more accurate application of common Systems Engineering processes that usually have a similar approach: simulating a high level conceptual design activity is, indeed, possible to propose modularly the roadmap elements already linked between them simplifying also the following design activities. In addition, for the reasons explained before, a roadmapping methodology able to support and ease the managing of a SoS (i.e. in the context of a mission-oriented ongoing large-scale collaborative programme) has to be a rational, data-based and normative roadmapping methodology.

Once this process is completed, all data need to be updated and (at least periodically) reviewed. This implies that, with time, the maturity of the elements involved in the roadmap has to increase. In addition, the properties of systems and missions have to be updated if some improvements have been achieved. Important is the role in this phase of the database and of its integration with the roadmap methodology. Indeed, the update and review process is an iterative and recursive process. The final result of this iterative and recursive process is the final optimized technology roadmap. At the end of this process is possible to outline Technology Maturation Plans and to provide them to the final users. Technology development plan identifies key technological advances and describes the steps necessary to bring them to a level of maturity that will permit them to be integrated successfully into a program/project [53].

III. TRIS: methodology and tool for Technology Roadmaps

Accordingly to a widely accepted definition, a roadmap can be defined as a summary of science and technology plans in the form of maps and the roadmapping process is the process aimed at deriving the roadmap [54]. A technology roadmap is the result of complex and strictly interwoven activities, which pursue the identification and selection of technologies, missions, capabilities and building blocks to eventually support strategic decisions.

A technology roadmap consists therefore of different elements, according to agencies' or companies' needs and constraints, which may be summarized as follows [55][56][57]:

1) *Operational Capability* (OC), defined as a high level function responding to a mission statement (or more generally to a Research Study Objective);
2) *Technology Area* (TA), defined as a set of technologies that accomplish one or more OCs and usually is subject of further sub-categorizations (i.e. Technology Subject and Technology);
3) *Building Block* (BB), defined as a physical element that may include several technologies, combined together to achieve certain functions (OCs);
4) *Mission Concept* (MC), defined through a mission statement and made up of BBs, in order to implement several OCs and make use of certain technologies.

The proposed methodology has a significant number of constraints and variables, which are highly interrelated and do require a proper software toolchain that has been ad-hoc developed to make simpler and more user-friedly the application and exploitation of the methodology itself. TRIS, which stands for Technology RoadmappIng Strategy, is the name of both the methodology that lays behind the tool and software tool itself. Fig. 1 describes the overall TRIS methodology, which proceeds through sequential steps from *Roadmap elements definition and characterization* (first step) to *Results evaluation* (sixth step).

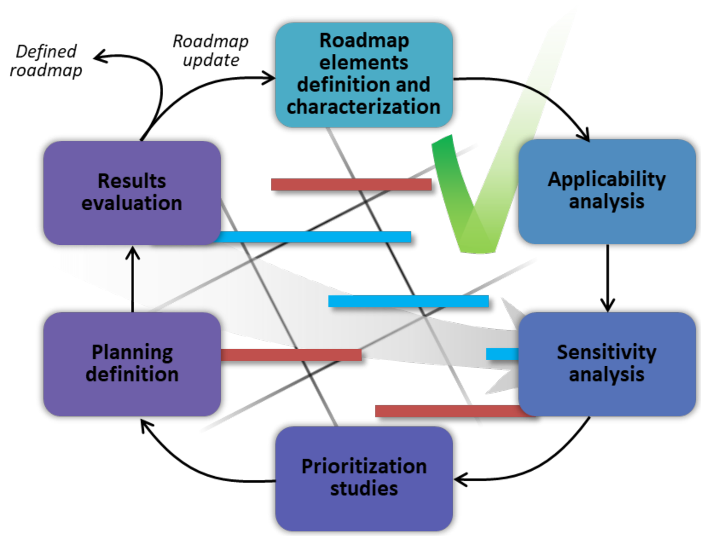

Fig. 1. TRIS methdology

Stakeholders' needs, regulations and other constraints as, for example, the operative environment, are important inputs for the identification of the four pillars. BBs and technologies stem from the product tree, while for the capabilities, defined as performance requirements, additional trade studies have to be performed to derive the final list that combines functional tree results with performances. As far as MCs are concerned, taking into account advancements and fundings, MCs can be subdivided into three different categories (i.e. operational MCs, demonstrative MCs and technology maturation activities) and derived accordingly on the basis of the modes of operations of the reference scenario, the basic Mission Phases and the technology maturation activities (such as tests and verification campaigns) [57][58].

Once the lists of the four pillars are complete, other steps need to be accomplished to generate the technology roadmap. The methodology considers as crucial characteristics the relationships between the four pillars, which according to their definition are strictly related one another. Starting from any of the four pillars, all the others can be derived through a logical process that eventually suggests the right sequence of MCs to reach the desired TRL increase path, as shown in Fig. 1. The fundamental analysis to link the four pillars is the *Applicability analysis* (TRIS second step), which is here intended as a way to detect and describe correlations between elements. Through the applicability analysis it is possible to specify if connections between elements are required, applicable or not applicable (in this case quite obviously no connections do exist between elements), as shown in Fig. 2.

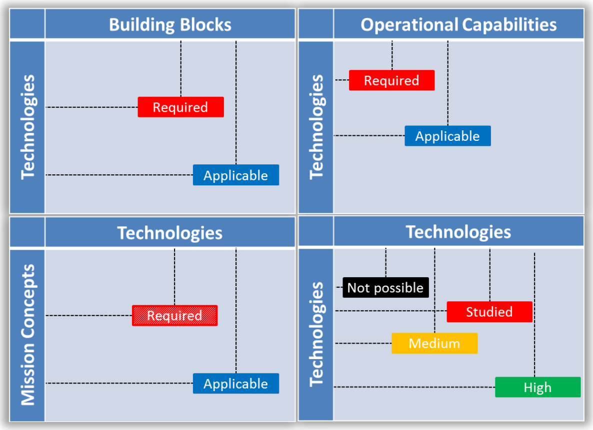

Fig. 2. TRIS: Applicability Analysis

Required, applicable and not applicable are considered as “labels” and weighted through the *Sensitivity analysis* (TRIS third step) to represent stakeholders’ expectations.

The applicability analysis is also strictly related to the *Prioritization studies* (TRIS fourth step), where further methods have been introduced to prioritize technologies and MCs. These methods are able to rank technologies and MCs according to stakeholders needs, providing also post-processing results for decision makers.

Technologies’ prioritization study consists of following steps (see Fig. 3):

1. technologies are listed but not ordered according to any ranking criterion;
2. prioritization criteria and methods are chosen. A prioritization method has been presented in [59][60][61] to limit stakeholders’ involvements in the prioritization process and rank the technologies into various lists, according to the selected order of criteria, the method of prioritization itself and constraints;
3. identification of the Figure of Merits (FoMs) to evaluate the lists of ranked technologies. Example of significant FoMs that have been considered in literature [59][60][61] are: TRL cost-effectiveness, cost increase and probability of failure;
4. evaluation of the ranked lists of technologies according to the identified FoMs.

Fig. 4 provides the user with a deeper insight into the prioritization studies applied to technologies. In particular the green column highlights the main steps of the section dedicated to criteria and methods, while the purple column highlights the combination of FoMs to eventually get the rank list of technologies.

As far as criteria and methods are concerned, in literature, many prioritization methods do exist [62] to support decision makers activities. Even if, depending on specific agencies or industrial needs, tailored methods have been developed, some examples of prioritization criteria have been in-depth investigated and are widely accepted: Multi-voting Technique, Strategy Grids, Nominal Group Technique, Hanlon Method and Prioritization Matrix.

The proposed final method is a hybrid version of the prioritization matrix, where a decision tree is used to find every possible criteria combination and choose the optimal solution.

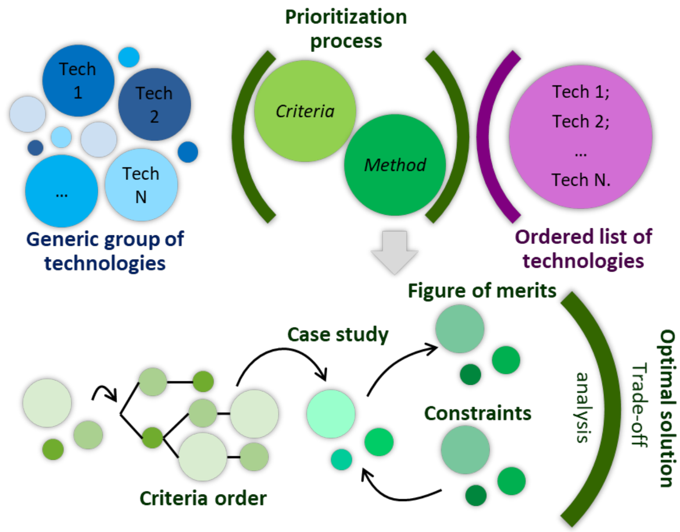

Fig. 3. TRIS: prioritization studies applied to technologies

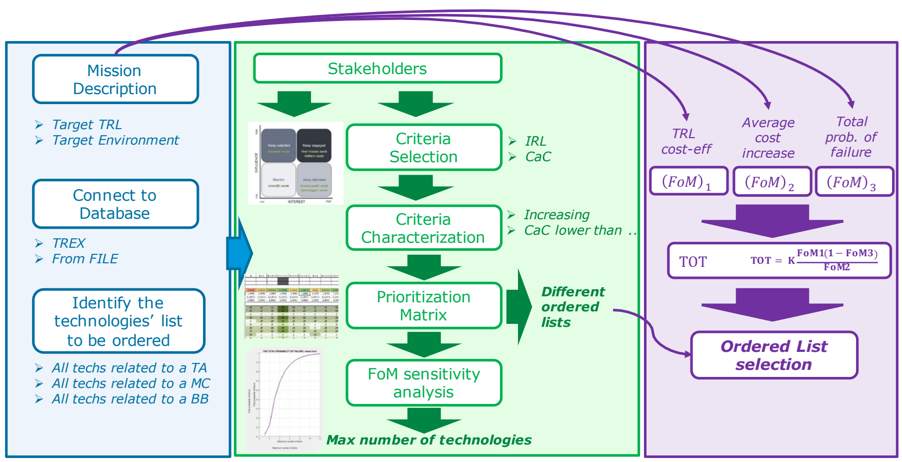

Fig. 4. TRIS: insight into prioritization studies applied to technologies

As far as FoMs are concerned, three FoMs have been defined:

- ○ TRL cost-effectiveness (FoM_1);
- ○ Average costs increase (FoM_2);
- ○ Total probability of failure (FoM_3).

The first FoM (i.e. TRL cost-effectiveness) is defined as follows:

$$FoM_1 = \frac{\sum_i \Delta TRL_i}{\sum_i \Delta costs_i} \tag{1}$$

TRL cost-effectiveness is defined as the ratio between the sum for each technology (i) of the TRL increase achieved (i.e. $\sum_i \Delta TRL_i$) with respect to the sum (again for each technology (i)) of the costs related to this increase. The second and the third FoMs refer to the average costs increase (FoM_2) and the total probability of failure (FoM_3), as functions of the risk in implementing a certain technology or a certain mission, respectively. Risk is defined as the product of the likelihood of failure by the consequences of this failure [63].

Fig. 5 shows the relationship between FoM_2, FoM_3 and risk, depicting the steps required to obtain these FoMs from the available data, which are: the TRL (actual TRL and TRL to be reached), the environment for which the technology has been originally conceived, and the environment in which the technology will be exploited. Please, notice that the two environments mentioned above may not coincide, and the target environment may be simpler, more complex, or with the same characteristics of the original environment [15]. To evaluate the risks, the Advancement Degree of Difficulty (AD^2) has been considered and estimated for each technology, as reported in Fig. 6. The AD^2 expresses the difficulty associated to the target of increase the TRL of a certain technology. It is a nine-level metric, which measures the effort required to further improve the TRL of a technology, considering the new design objectives, as well as risks and consequences on the design. Fig. 5 provides a definition of the AD^2 levels and the associated risk according to [58].

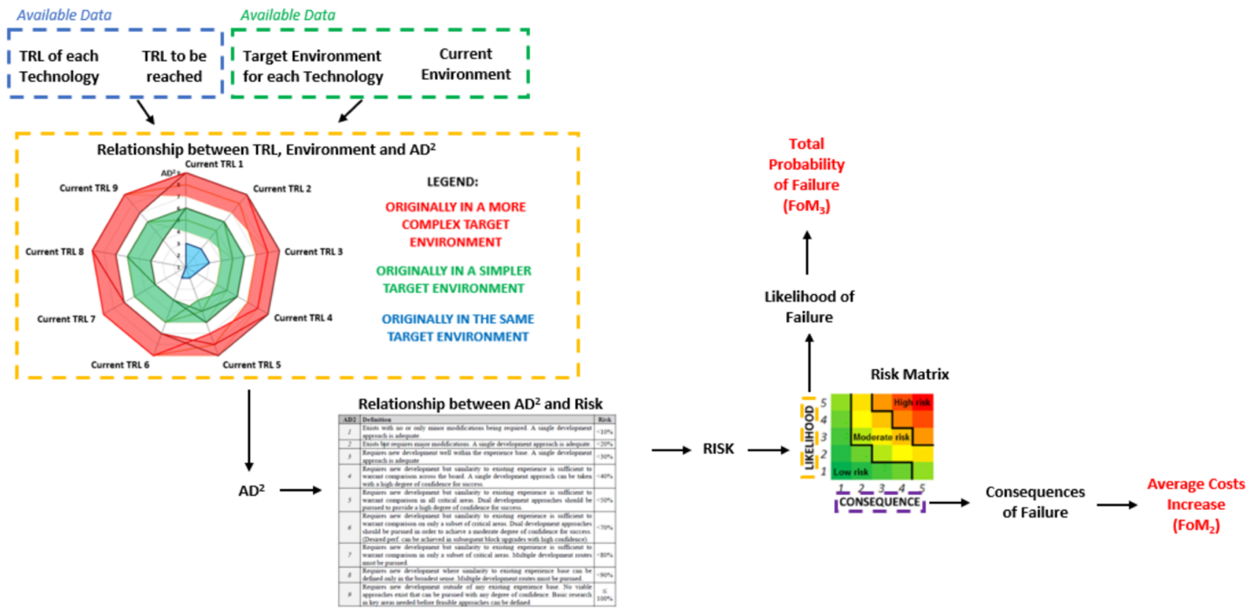

Fig. 5. TRIS: prioritization studies applied to technologies to define FoM2 and FoM3 as a function of risk

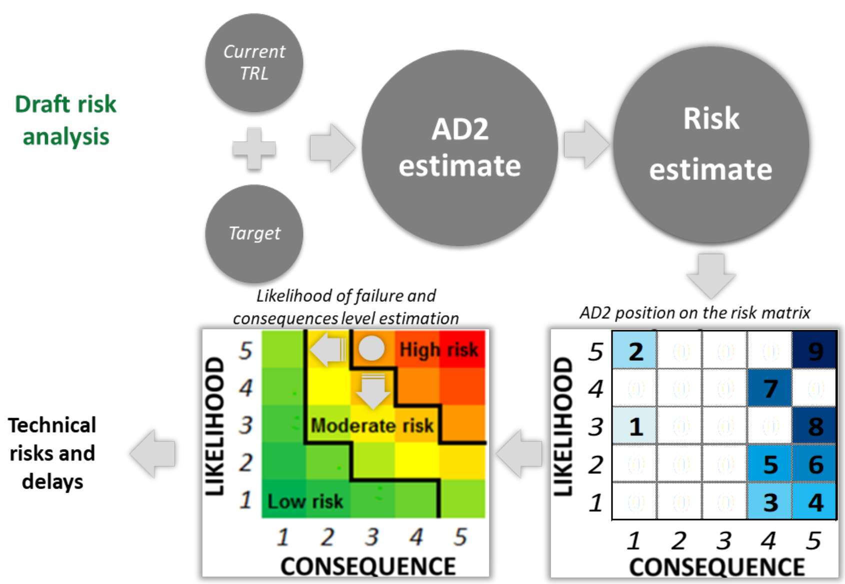

Fig. 6. TRIS: methdology to estimate the risks of a TRL target to reach on the basis of AD2

Unlike technologies prioritization studies, MCs' prioritization study consists of the following steps:

1. Identification of the complete set of possible activities and missions. Activities and missions shall cover all TRL transitions, starting from low TRL up to high TRL. Specifically, activities refer to low TRL transitions, while missions refer to high TRL transitions, which occur in not controlled environment;

2. Rank of activities and missions according to the following criteria:
    a. minimization of the MCs' costs;
    b. maximization of Earth surface proximity operations;
    c. maximization of the number of modes of operations to test during the same activity/mission (i.e. minimization of the number of overall required MCs to cover all functionalities);
    d. maximization of the number of technologies to test during the same activity/mission (i.e. minimization of the number of overall required MCs to cover all technologies in the list).

By combining technologies and MCs' prioritization studies, it is possible to derive one or more TRL increase paths for the technologies under study. Fig.9 schematically shows the main steps that have to be taken to generate the TRL increase paths within the *Planning definition* (TRIS fifth step).

Prior to the generation of TRL increase paths, the following crucial activities have to be accomplished:

1. *budget analysis* to prune the list of technologies on the basis of the available budget;
2. *MCs selection* to pursue a step by step approach for the TRL increase path definition (i.e. one MC has to achieve one single TRL transit);
3. *Schedule definition*, to combine the final MCs with a time reference.

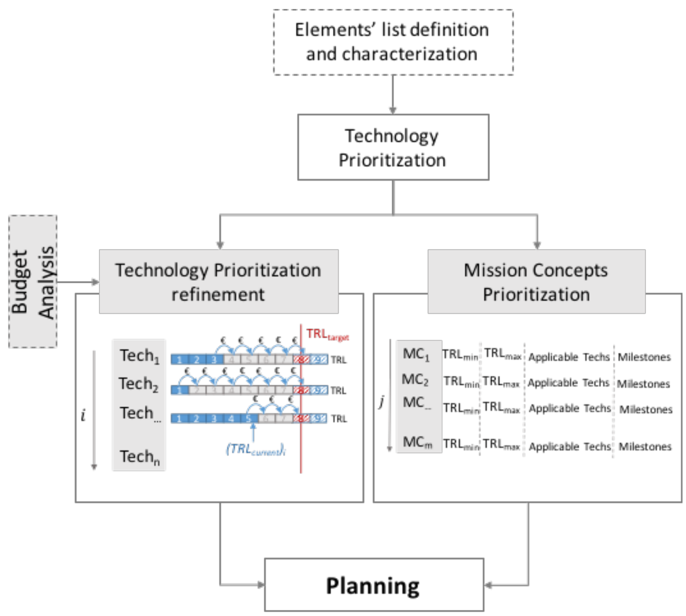

Fig. 7. TRIS: preparation to planning activity

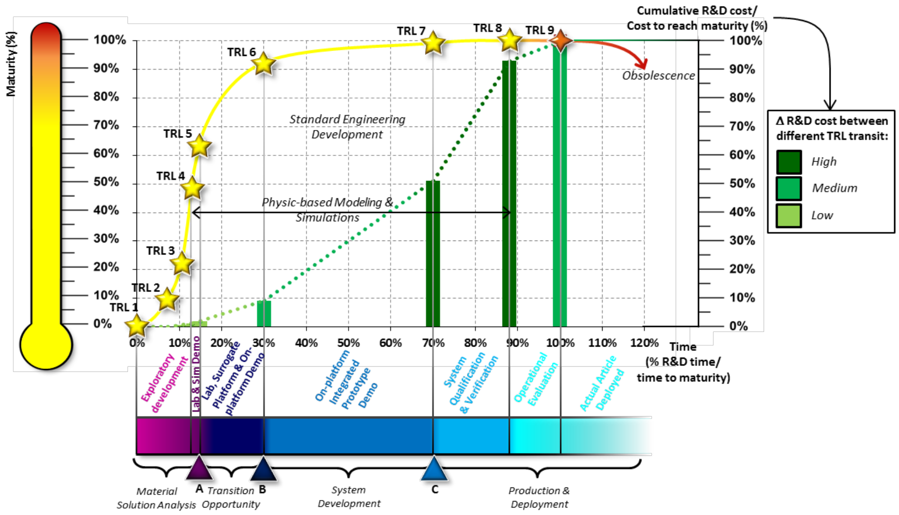

Fig. 8. Statistical analysis for the variation of costs with TRL and TRL with time of the program

The budget analysis is a crucial activity for the entire roadmapping process, especially considering that the overall available budget is one of the hardest constraints. Indeed, depending on the available budget, the theoretical list of technologies can be pruned or the goals of the mission can be reduced. In particular, thanks to past studies carried out by the authors, the available budget can be spread all over the lists of technologies on the basis of the TRL variations theoretically planned. Fig. 8 presents the TRL variation as function of the design phases and their time duration (x-axis) combined with technology maturity (left-hand side) and cumulative costs (percentage of R&D costs, right-hand side). Light green indicates low to moderate cost to advance from one TRL to the next one. Dark green indicates high cost to advance from one TRL to the next one. Thanks to this semi-emprical approach, the amount of budget necessary for each TRL transit of each of the technologies in the list can be evaluated. In case the available budget is not sufficient to cover all the TRL transits, two different solutions might be adopted:

1. the theoretical list of technologies is pruned and the technologies with the lowest level of priority are no more considered into the roadmap generation process. This solution is adopted when the stakeholders are absolutely interested in increasing as much as possible the TRL of the technologies even if this might reduce the number of technologies to be improved.
2. The TRL target already fixed at the beginning of the analysis is reduced in order to allow to the highest possible number of technologies to increase their readiness level. This solution is typically adopted in case the stakeholders privilege a more homogeneous incremental approach.

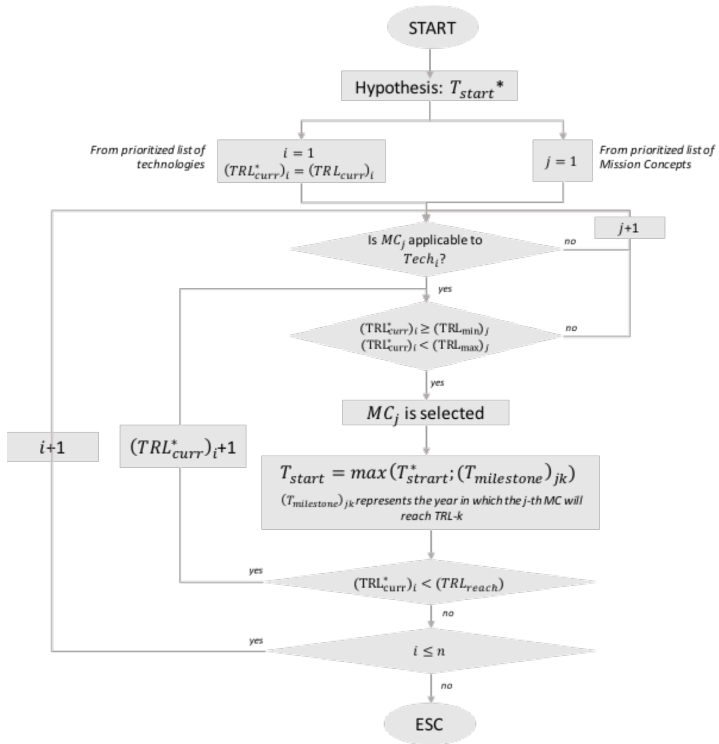

Fig. 9. TRIS: planning algorithm

Once the technologies list has been refined and the MC list has been prioritized too, it is necessary to move to the following step of the methodology, i.e. the Planning. Following the logical path presented in Figure 9, for each technology, according to the ranked list, a set of mission concepts (operative missions, demonstrative missions or simply activities) are selected and planned. Basically, for each TRL transit, the algorithm suggests the MCs having the highest ranking and compatible with the technology under investigation and in line with the considered TRL transit. Please, notice that in this approach, each MC can fulfill a unitary TRL transit only but a single MC can be used to improve more than a single technology, after positive compatibility check.

The Planning phase is then completed through the suggestion of a feasible timeline that is mainly driven by the milestones of the already planned activities and operative missions. In case of demonstrative missions or suggested activities, reasonable starting dates shall be hypothesized while the duration can be estimated using Fig. 8.

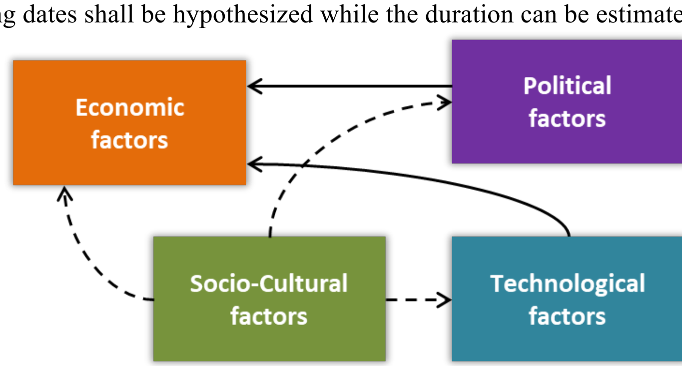

Fig. 10. TRIS: results evaluation

At the end of the *Planning definition*, a nominal planning can be proposed and additional studies can be performed to verify it and propose corrections. In this framework, the following activities may be particularly significant:

- verification of out-of-nominal situations (e.g. PEST, Political, Economic, Socio-cultural and Technological analysis [59]), as highlighted in Fig. 10, which schematically shows TRIS sixth step, *Results evaluation*;

- evaluation of the impact on the results of stakeholders' inputs to analyze (sensitivity analysis), for instance, how the variation of the desired TRL to reach can affect the results;
- preliminary risk analysis to estimate the risks in terms of likelihood and consequences of the TRL target to reach on the basis of the AD^2 [59][60], as depicted in Fig. 6.

IV. Intermediate eXperimental Vehicle, IXV: a case study for TRIS

In order to have a validation of the entire workflow and of the data stored in the Database, the case of the Intermediate eXperimental Vehicle has been selected. Freezing the Database to 2006, the authors tried to envisage a roadmap for a subset of enabling technologies.

Table 1. IXV TPS (Thermal Protection System) data

ID – Technology name	TRL		Costs (Mio €)	Time (years)
	Start (2006)	*End (2015)*	*2006-2015*	*2006-2015*
1 - FEI with low ultimate temperature	7	8	1,5	2,2
2 - FEI with medium ultimate temperature	**7**	**8**	**1,5**	**2,2**
3 - FEI with high ultimate temperature	**6**	**8**	**1,6**	**7,2**
4 - SPFI with high ultimate temperature	**5**	**8**	**4,4**	**9,1**
5 - Metallic (TiAl) TPS with medium ultimate temp.	4	8	13,8	9,3
6 - Metallic (ODS) TPS with high ultimate temp.	4	8	13,8	9,3
7 - Ceramic TPS with high ultimate temp.	**5**	**8**	**17,21**	**9,1**

Indeed, even if Europe already has access to space, it has a limited experience associated with hypersonic, (re)-entry and landing vehicles on Earth or on other celestial bodies with an atmosphere. Among various initiatives, the IXV experiment [14] has to be mentioned as a real mission of utmost importance. IXV performed a successful earth-atmosphere re-entry flight experiment following a sub-orbital flight path. Despite this effort, the need of plans to increase the European presence in the market related to the field of hypersonic and re-entry space transportation systems is even more compelling in recent years. In the remaining of the section the main results of the application of the comprehensive methodology applied to IXV are presented.

The analysis focuses only on Thermal Protection System (TPS) technology area because TPS data were available in literature. All other IXV enabling technologies were therefore disregarded. Table 1 summarizes the available initial data. The list of TPS technologies includes all technologies that were considered at the beginning of the program (2006) from literature review, as well as their initial and final TRL. The available budget for all TPS technologies was 25 M€. The total cost at completion was then split between the listed technologies, keeping in mind that technologies are different and that their maturity level in 2006 was different. A statistical analysis was then performed to collect and analyze crucial data to be then able to estimate the costs of the transition from one TRL to the next one and this was a precious outcome. Main result of the statistical analysis is shown in Fig.9.

It is worth underlying that the population of the statistical analysis combines all technology areas of the hypersonic, re-entry and space transportation systems. This means that one graph includes all technology areas thus diminishing the accuracy of the results, which could be enhanced in case of single graphs for each technology area.

Applying the process to the IXV case-study, one of the first significant results obtained was the prioritization of technologies. Table 2 reports the list of ranked technologies as output of the tool. The technologies were ranked on the basis of the following criteria:

1. High applicability in BBs;
2. Low AD^2;
3. High applicability in OCs;
4. Low TRL.

Taking into account as constraint the overall budget limitation of 25 M€, the final list of ranked technologies was eventually cut and only the first four technologies were considered enabling. The final list of technologies was exactly the same list of technologies integrated on board IXV.

Table 2. IXV TPS list of ranked technologies

Rank	*ID – Technology name*	*Impact*
1	4 - SPFI with high ultimate temperature	Enabling
2	3 - FEI with high ultimate temperature	Enabling
3	2 - FEI with medium ultimate temperature	Enabling
4	7 - Ceramic TPS with high ultimate temp.	Enabling
~~5~~	~~5 - Metallic TPS with medium ultimate temp.~~	~~Enhancing~~
~~6~~	~~6 - Metallic TPS with high ultimate temp.~~	~~Enhancing~~
~~7~~	~~1 - FEI with low ultimate temp.~~	~~Enhancing~~

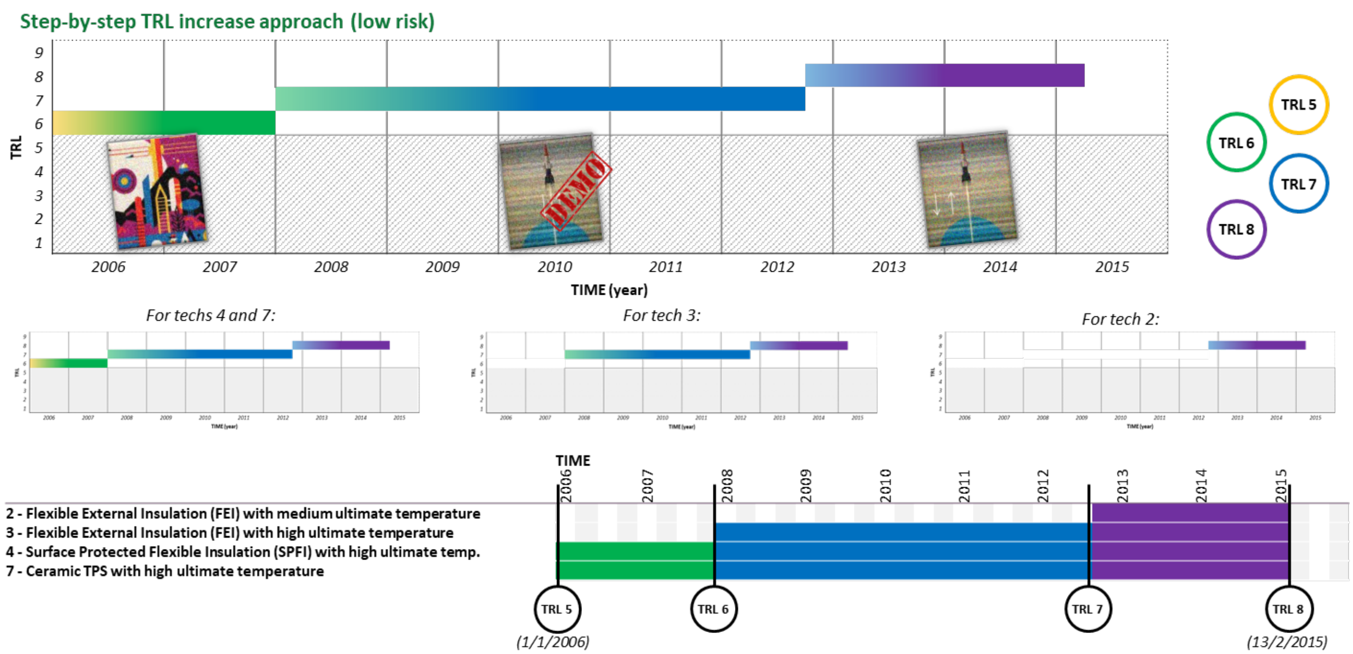

Fig. 11. Pure technical approach: roadmap in three steps, one per each TRL

Depending on the constraints on MCs, two different results in terms of TRL increase paths were provided by the tool. Initially no constraints for MCs were considered. This hypothesis implied that all MCs were theoretically available, even though some of them were not yet approved, under approval or even not yet flight proven. This approach has to be considered as a pure technical approach. Then constraints for MCs were introduced to pursue a different strategy, not a pure technical approach but for sure a more realistic approach. Results in terms of suggested incremental TRL paths were very different for the two approaches. For the pure technical approach the output of the tool was that Point-to_Point (P2P) hypersonic missions could perfectly fit with the maturation path of the TPS technologies. The tool indicated two alternatives: 1) a roadmap in three steps, one per each TRL (see Fig. 11); 2) a roadmap in two steps, one to reach TRL 6 and one to move from TRL 6 to TRL 8.

For the second approach, the more realistic one, which did consider Missions Concepts costs, the output of the tool was a sub-orbital re-entry mission for the maturation path of the TPS technologies. The tool indicated two alternatives: 1) a roadmap in three steps, one per each TRL; 2) a roadmap in two steps, one to reach TRL 6 and one to move from TRL 6 to TRL 8.

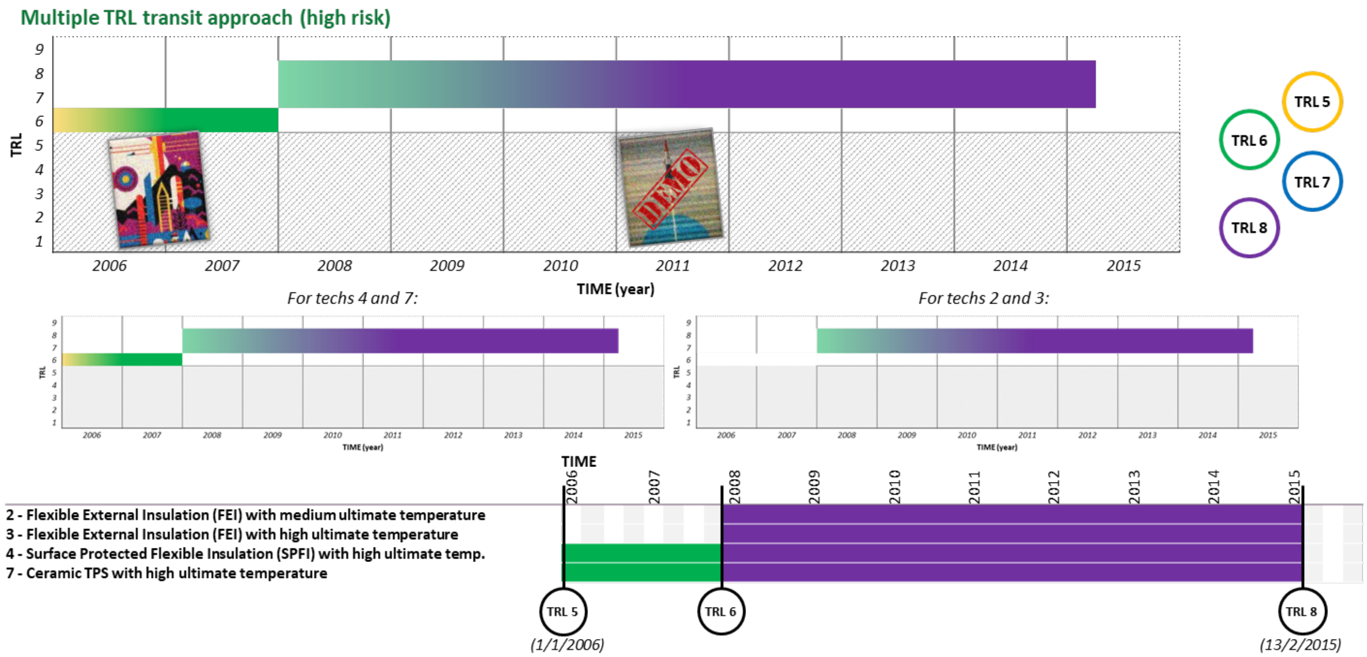

Fig. 12. More realistic approach: roadmap in two steps.

Eventually, as far as the results evaluation phase is concerned, a sensitivity analysis has been performed to understand the consequences of different TRLs as targets to reach. Main results are shown in Table 3.

Table 3. TRL sensitivity analysis

TRL to reach	N of TRL transit	Techs involved	Technologies at TRL	Techs already at TRL	Cost (Mio€)	Cost (% of the budget)
8	9	4	4	0	24.74	100%
7	8	3	3	2	24.52	99%
6	6	4	4	3	3.00	12%
5	2	2	2	5	1.18	5%

Table 4. AD2 level

Target environment		Simpler					Same	Complex				
TRL to reach		1-2	3-4	5	6-7	8-9	1-9	1-2	3-4	5	6-7	8-9
Current TRL	1	4	5	6	6	6	3	7	8	9	9	9
	2	4	5	6	6	6	3	7	8	9	9	9
	3	5	4	5	6	6	3	8	7	8	9	9
	4	5	4	5	6	6	2	8	7	8	9	9
	5	6	5	4	5	6	2	9	8	7	8	9
	6	6	6	6	4	4	2	9	9	9	7	7
	7	6	6	6	4	4	1	9	9	9	7	7
	8	6	6	6	6	4	1	9	9	9	9	7
	9	6	6	6	6	4	1	9	9	9	9	7

AD2 level

In addition, a preliminary risk analysis has been completed to account for the extra budget that could have been allocated to the project on the basis of the AD^2 and the methodology presented in Fig. 6. Thanks to this analysis a total cost increase of about 0.6 M€ was estimated, taking into account the AD^2 level shown in Table 4. Main results are reported in Table 5.

Table 5. Results of the preliminary risks analysis

ID	*Applicable Technologies*	Target environment comparison	AD2	Total probability of failure	Maximum allocated costs increase
~~1~~	~~*FEI with low ultimate temperature*~~	~~Same~~	~~3~~	~~12%~~	~~10%~~
2	*FEI with medium ultimate temperature*	Same	3	12%	10%
3	*FEI with high ultimate temperature*	Same	2	98%	2%
4	*SPFI with high ultimate temperature*	Same	2	98%	2%
~~5~~	~~*Metallic (TiAl) TPS with medium ultimate temperature*~~	~~Same~~	~~2~~	~~98%~~	~~2%~~
~~6~~	~~*Metallic (ODS) TPS with high ultimate temperature*~~	~~Same~~	~~2~~	~~98%~~	~~2%~~
7	*Ceramic TPS with high ultimate temperature*	Same	2	98%	2%

V. Conclusion

To overcome both the lack of data and of a common and shared vision within the areas of hypersonic, re-entry and generally future reusable space transportation systems, the study presents and discusses a comprehensive methodology, which pursues the following main objectives:

- to collect and to store in a rational and structured way data about past hypersonic, re-entry and space transportation systems studies, initiatives and projects;
- to provide statistical trends on the basis of the available data, for the different missions and vehicle design architectures;
- to suggest incremental paths to achieve defined target missions, OCs, BBs or technologies' maturation, correlated with cost and time budgets.

The methodology has been implemented through two software tools: HYDAT and TRIS. IXV has been selected as case-study to validate the methodology and the tools.

Comparing the IXV project with the nominal roadmap, TRIS has proved to be able to identify IXV TPS technologies, a similar time schedule and a similar final budget, through the selection of similar MC (i.e. a suborbital re-entry mission in inner space). The tool appear therefore to be reliable and flexible, and potentially useful for users and stakeholders. Users and stakeholders are required to provide inputs to enrich the tools with their inputs (see Fig. 13) but are also expected to benefit from the tool's outputs in terms of decisions of technologies and missions (programs) prioritization, suggestion of potential (new) MCs and BBs and of course technology roadmap generation. In particular, it is worth underling the crucial role that the suggestion of potential (new) MCs and BBs could play in the overall strategic development plans.

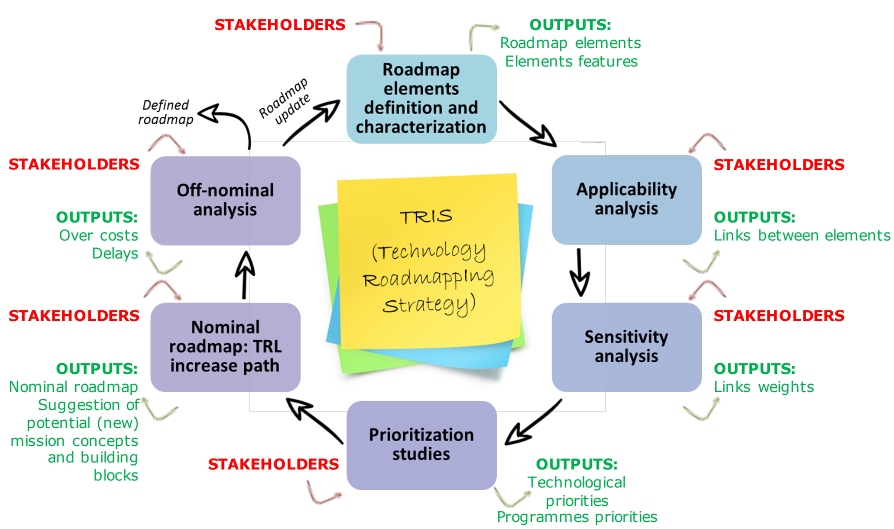

Fig. 13. Expected inputs and outputs of the application of the methodology

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