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Space Systems Engineering Tools for Technology Roadmapping Activities: TRIS, Technology Roadmapping Strategy, and HYDAT, Database on Hypersonic Transportation Systems

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Abstract

A technology roadmap is the output of the technology roadmapping process, a complex and continuously evolving process, which aims at selecting technologies, mission concepts, capabilities and building blocks to pursue incremental paths to increase the Technology Readiness Level, according to specific strategic plans. Technology roadmaps are crucial not only to illustrate the technologies' procurement plan for specific missions in the future, but also the achievement for Europe of technological milestones enabling operational capabilities, essential for current and future space missions. Coordination of requirements and funding sources among all European stakeholders (ESA, EU, National Agencies, Industries) is one of the objectives of technology roadmaps. The paper presents the results of a research activity carried out by Politecnico di Torino in support to the work on-going at ESA to elaborate technology roadmaps for the hypersonic and (re-)entry space transportation systems' domain. Traditionally the approach has always been based on workshops and brainstorming. The idea at the basis of the research activity has been the development of a flexible and rational methodology to generate technology roadmaps to better support strategic decisions in combination with traditional methods. The research activity thus focuses on the development of an innovative methodology to derive, track and manage the technology roadmaps' basic pillars (Technology Areas, Operational Capabilities, Mission Concepts and Building Blocks) and on the implementation of the methodology itself into two ad-hoc tools: TRIS, Technology Roadmapping Strategy, and HYDAT, Database on Hypersonic and (re-entry) transportation systems. TRIS is a versatile software tool that implements the objective methodology for technology roadmaps' derivation and update. HYDAT is a smart database, able to collect, categorize and analyze data to support technology roadmaps for (re-)entry missions and reusability applications. In addition, HYDAT can support hypersonic and (re-)entry conceptual design activities. First, the paper describes the main settings of the database that manages all relevant initiatives for technological development of hypersonic and (re-)entry systems, categorizing them according to the roadmap pillars. Secondly, the paper presents TRIS, the tool used to derive, track and manage the pillars and consequently to generate the technology roadmaps. Eventually, the paper presents and discusses the results obtained by the application of HYDAT and TRIS to IXV (Intermediate eXperimental Vehicle), analysing main activities expected in the near and far future to enhance hypersonic and (re-)entry technologies and proposing a TRL increase path in terms of missions and activities to perform, and in which schedule to carry out them.

Keywords: Technology Roadmap, Future Reusable Space Transportation Systems

Acronyms/Abbreviations

BB	*Building Block*
GUI	*Graphical User Interface*
HYDAT	*Hypersonic Database*
IXV	*Intermediate Experimental Vehicle*
MC	*Mission Concept*
OC	*Operational Capability*
TA	*Technology Area*
TS	*Technology Subject*
TRIS	*Technology Roadmapping Strategy*
TRL	*Technology Readiness Levels*

1. Introduction

The paper describes a comprehensive methodology for technology roadmaps generation and update to support the European Space Agency in defining new strategies in the framework of hypersonic, re-entry and future reusable space transportation systems. Indeed, in the last decade, the interest in this kind of systems has been noticeably increased, considering not only the number of new technological developments relevant to hypersonic flight, but also private commercial initiatives towards the same goal. Unfortunately, the efforts in research and development activities are seriously hampered by the lack of a shared vision on how to exploit the currently under development disruptive innovative technologies. A technological roadmap for hypersonic, re-entry and future reusable space transportation systems can be seen as the best answer to bridge this gap and provide the scientific and engineering community with a common strategy to reach the ultimate goal of reusable space transportation vehicles.

For this purpose, since 2016 Politecnico di Torino has been developing a comprehensive methodology able to collect data about past and current research, development and design activities, studies, experiments or projects related to the hypersonic transportation and to exploit the available data to generate Technology Roadmaps. This activity allows defining feasible incremental paths to increase the Technology Readiness Levels (TRLs) of crucial technologies, thus generating and eventually updating technology roadmaps for hypersonic, re-entry and future reusable space transportation systems.

The paper aims at providing the readers with a complete overview of the overall comprehensive methodology, starting from the description of HYDAT (HYpersonic DATabase) and TRIS (Technology RoadmappIng Strategy), two tools developed by Politecnico di Torino together with ESA, to support technology roadmap generation and update processes. HYDAT, a structured and flexible database collecting data for hypersonic and re-entry transportation systems, was introduced to the scientific community in 2017 [1] [2] [3]. In the same context, the results of the exploitation of TRIS in hypersonic and re-entry transportation domain, were presented and successfully applied [1] [2] [4].

HYDAT and TRIS are extensively described in Section 2, whereas Section 3 presents the results of the application of the methodology to the well known case-study of the Intermediate eXperimental Vehicle (IXV). Eventually in Section 4 main conclusions are drawn.

2. HYDAT and TRIS

2.1. HYDAT

In order to comply with all stakeholders' needs and expectations, HYDAT has been conceived, since the beginning, as a well-structured and organized collection of data, easily to be uploaded, modified and updated, with a user-friendly interface that will ease the input and output data management.

The structure of HYDAT (Database of Aerospace Hypersonic Initiatives) clearly mirrors its dual purpose. Indeed, first of all, HYDAT should support the Technology Roadmaps generation process and secondly, it should provide the users with the basis for multi-purposes statistical analyses, considered fundamental for the conceptual design activities. To facilitate data insertion, the Database is supported by a Graphical User Interface (GUI), developed in Matlab® environment, as shown in Fig. 1. The core of the database, where data are properly categorized and stored, exploits MS Excel®.

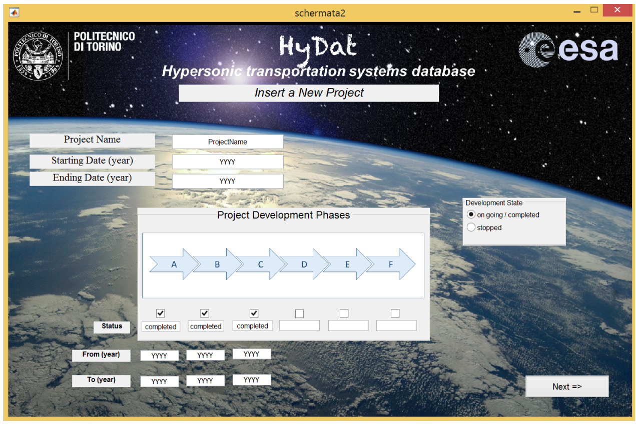


Fig. 1. Example of GUI of HYDAT

First of all, each project should be described in terms of schedule and budget. In particular, the user is invited to insert start and ending date for each project phases that has been completed. In case the project has not been already completed, the user is invited to indicate the reason why for the stop (economic, political, technical unfeasibility, etc…). In addition, the user can indicate whether all along the project life cycle, some important political events or organization changes happened (e.g., a Ministerial Conference) and, if possible, clearly state the delays and the change in the available budget. HYDAT, exploiting some statistics already stored in, suggests possible critical events during the project timeline. Of course, each time a new user is inserting a new critical event, the statistics is updated. In this context, it is also important that the user clearly indicates the leadership of the project and the partners' nationality. This will allow HYDAT to properly filter statistics of critical events on the bases of the involved countries. Moreover, considering that during the overall project life-cycle, some changes in the consortium may happen, the user should indicate whether one or more member states abandoned the project and the reason why.

Once the project has been described, the user should describe the mission in terms of operating environment, take-off and landing strategy and staging strategy and some additional details about the major mission phases.

This description can allow for a coherent data categorization within the database, resulting in more realistic statistical trends.

Once the mission is defined, it is possible to move to the definition of Technology Areas and related Technology Subjects to derive the list of Technologies, thanks to the combination of TS with relative technical characteristics. The technologies are generated through the exploitation of the Technology Areas and the Technology Subjects and all the possible combination with the technical characteristics. In particular, it has been supposed that in order to simplify the generation of technologies, three-level logic has been adopted. Thus, each technical characteristic can be required with a high, medium or low level. A proper GUI provides the user with the possibility of selecting the characterizing performances (i.e. Technical Characteristic) with the possibility of indicating the numerical value or the performance level required. The technologies should be characterized in terms of TRL, development time and costs. In case these data are not available, preliminary estimations based already inserted data and on high level estimation algorithms, a modified version of those proposed for Space Exploration [5] [6] is performed.

Besides the fact that HYDAT has been conceived for the specific aim of supporting the roadmap generation process for hypersonic, re-entry and future reusable space transportation systems, it would be a precious tool in support of design activities. HYDAT can provide the basis for generating statistical trends at different design levels, from project level up to technology level and thanks to the categorization strategy directly derived from the roadmap generation process methodology. This tool would be very useful especially during the conceptual design phase, when very few elements ae known but it is very important to have the very first numerical estimations of some parameters.

Thus, the second major objective pursued by HYDAT is the creation of a common platform in which data can be stored to be then exploited for the generation of statistics. The possibility of exploiting statistical data to initialize the conceptual design activities is a crucial added value especially for the design and development of a pretty new hypersonic vehicle. Differently from the interface with the roadmap tool, in this case the connection between HYDAT and the Conceptual Design Tool is quite more complex, implying a dedicated graphical interface.

2.2. TRIS

TRIS is a tool that implements a comprehensive methodology to derive and update 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 this roadmap [7]. Thus, a technology roadmap is the output of a particular kind of process aimed at identifying and selecting technologies, missions, capabilities and systems according to specific strategic plans. For simplicity, a generic roadmapping process consists of "application" (i.e., the roadmapping methodology) and "results of the application" (i.e. the roadmap).

A technology roadmap may consist of different elements, according to agencies' or companies' needs and constraints, but, generally, four pillars can be summarized as follows [8] [9] [1]:

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 methodology for roadmap definition and update is based on System Engineering tools and theory, which are typical of conceptual design processes. 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 advancement and funding [6], MCs can be subdivided into three different categories (i.e. operational MCs, demo MCs and technology maturation activities) and derived accordingly on the basis of the usual and more sizing modes of operations of the reference scenario, the basis Mission Phases and the technology maturation activities (such as tests and verification campaigns).

Once the lists of the four pillars are complete, other steps need to be accomplished to generate the technology roadmap. According to traditional approaches, technology roadmaps can be created on the basis of workshops, brainstorming, meetings, surveys, etc.. The idea that lies behind the present work is to develop a rational and objective methodology to generate technology roadmaps to better support strategic decisions in combination with traditional methods.

The innovative methodology considers as crucial characteristic 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. 2.

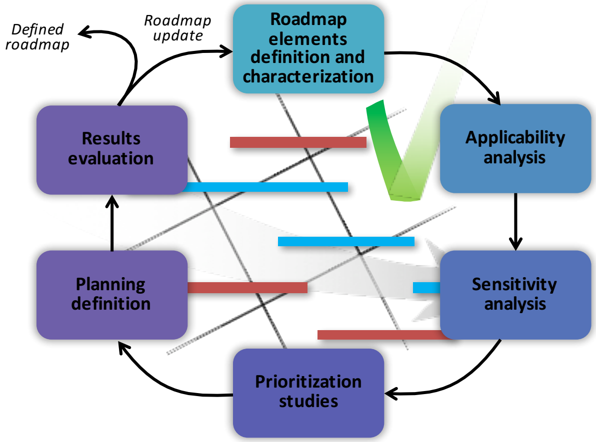


Fig. 2. TRIS methodology

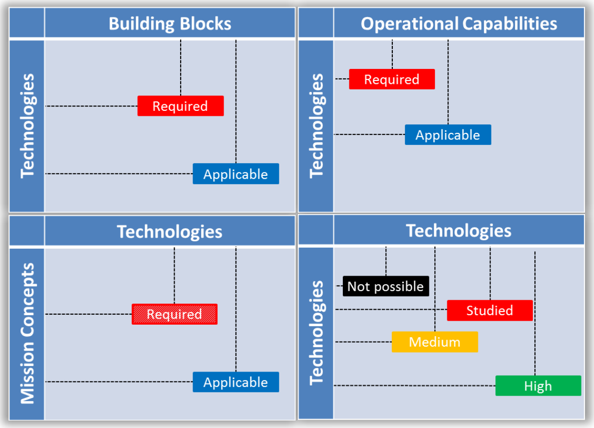


Fig. 3. TRIS: Applicability Analysis

The methodology has a significant number of constraints and variables that have to be considered and to simplify its application an ad-hoc toolchain has been developed. Indeed, through an ad-hoc studied toolchain involving MS Excel and Matlab, this process has been implemented in a simple and user-friendly tool able to implement the methodology and to obtain the TRL increase path only asking for a few inputs (e.g. the final budget available, the target environment the acceptable Integration Readiness Level, IRL).

One of the fundamental tools to link the four pillars is the *applicability analysis*, which is here intended as a way to detect and describe correlations between couples of elements. Through the applicability analysis it is possible to specify if connections between couples of elements are required, applicable or not applicable (in this case quite obviously no connections do exist between the couple of elements), as shown in Fig. 3.

Required, applicable and not applicable are considered as "labels" and weighted through the *sensitivity analyses* to clearly represent stakeholders' expectations. The weights of these labels depend on three crucial parameters:

1. the pseudo-TRL, which is the parameter used to size the maturity of OCs and defined as a weighted average of required and applicable technologies TRL);
2. the most required/applicable technologies over BBs, which is the sum of two products: the number of the required BBs multiplied by the required label's value and the number of the applicable BBs multiplied by the applicable label's value;
3. the most required/applicable technologies over OCs, which is the sum of two products: the number of the required OCs multiplied by the required label's value and the number of the applicable OCs multiplied by the applicable label's value.

The numerical value of the weights for required and applicable labels may range between 0,01 and 2. The most effective couple of numerical values for required and applicable labels shall guarantee the largest numerical difference between estimated pseudo-TRL, most required/applicable technologies over BBs and most required/applicable technologies over OCs. This goal allows for an easier comparison of the results, as the user can more clearly appreciate the main differences. An important feature of this "labels" is that they have to be related to the stakeholders. This characterization does not apply to MCs, that are more related to the budget and the schedule and are an important brick in the TRL increase path definition.

In the framework of the methodology, the applicability analysis is fundamental to map one brick, specifically TAs, onto the others and to provide information about these connections.

Applicability analysis is strictly related to the *prioritization studies*, where further methods have been introduced to prioritize technologies and MCs. These methods are able to rank technologies or MCs according to stakeholders needs, providing also post-processing results for decision makers.

Generally, technologies and MCs' prioritization study consists of following steps (see Fig. 4):

1. technologies are listed but not ordered according to any ranking criteria;
2. prioritization criteria and methods are chosen, usually through stakeholders' interactions and trade-off analyses. A prioritization method has been presented in [10] [11] [12] 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 [10] [11] [12] are: TRL cost-effectiveness, cost increase and probability of failure;
4. evaluation of the ranked lists of technologies according to the identified FoMs;
5. identification of the complete set of possible activities and missions;
6. rank of activities and missions to minimize costs, schedule, risks and the overall necessary pre-development activities or missions.

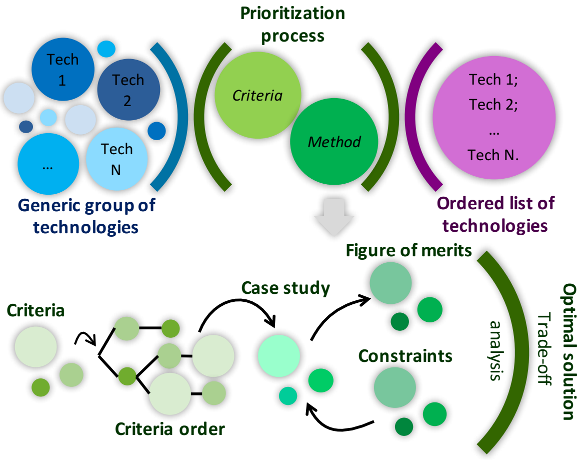


Fig. 4. TRIS: prioritization studies applied to technologies

By combining prioritizations studies, applicability analyses over different basic elements or between the same group of elements (as for example technologies versus technologies to study their reciprocal integration) and the main elements features it is possible to derive one or more TRL increase paths for the technologies under study.

Fig. 5 schematically shows the main steps that have to be taken to generate the TRL increase paths within the *planning definition* phase of the methodology.

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.

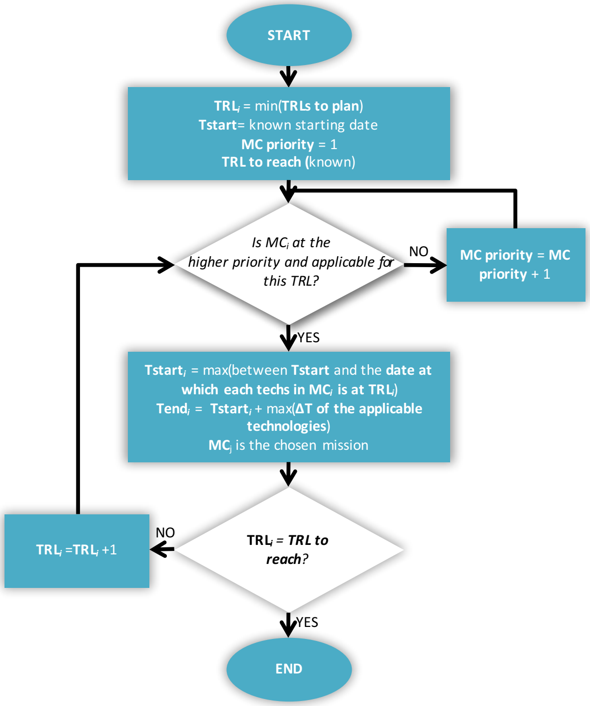


Fig. 5. TRIS: planning definition

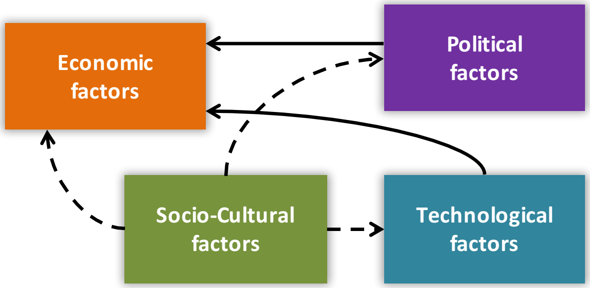


Fig. 6. TRIS: results evaluation

At the end of the planning definition phase, a nominal planning can be proposed and some 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 [13]), as highlighted in Fig. 6;

- 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 AD2 [14] [15], as depicted in Fig. 7.

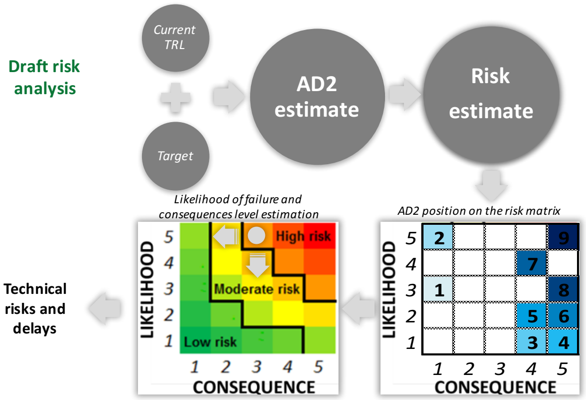
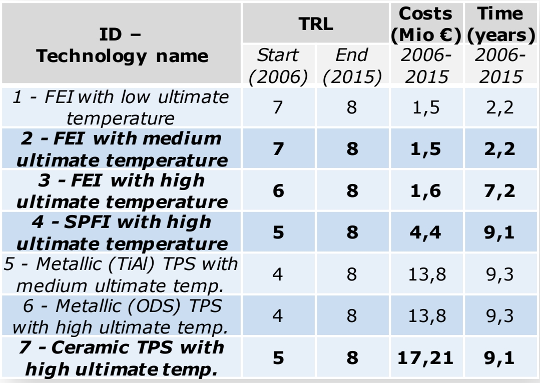


Fig. 7. Methdology to estimate the risks of a TRL target to reach on the basis of AD2

3. IXV: a case study for HYDAT and 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 (IXV) has been selected. Freezing the Database to 2006, the authors tried to envisage a roadmap for a subset of enabling technologies.

Table 1. IVX TPS 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 Intermediate eXperimental Vehicle (IXV) experiment [16] 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 TPS technology areas 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) according to from literature overview, as well as their initial and final TRL. The available budget for all TPS technologies was 25 MEuro (literature review). 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. 8.

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.

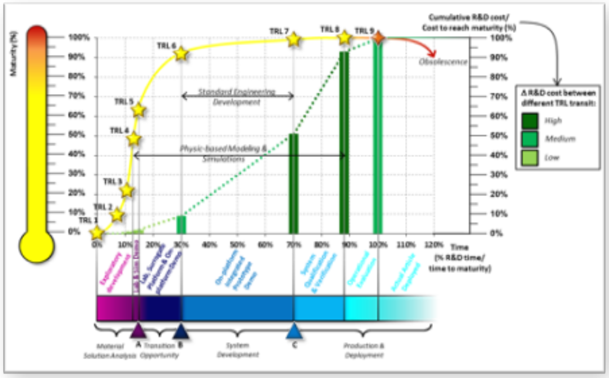


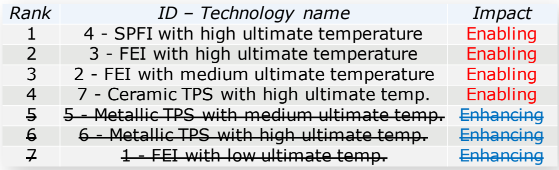
Fig. 8. Statistical analysis for the variation of costs with TRL and TRL with time of the program

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 Building Blocks;
2. Low Advancement Degree of Difficulty (AD2);
3. High applicability in Operational Capabilities;
4. Low TRL.

Taking into account as constraint the overall budget limitation of 25 Meuro, 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.



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~~

Depending on the constraints on mission concepts, two different results in terms of TRL increase paths were provided by the tool.

Initially no constraints for mission concepts were considered. This hypothesis implied that all mission concepts 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 constrains for mission concepts 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 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. 9); 2) a roadmap in two steps, one to reach TRL 6 and one to move from TRL 6 to TRL 8.

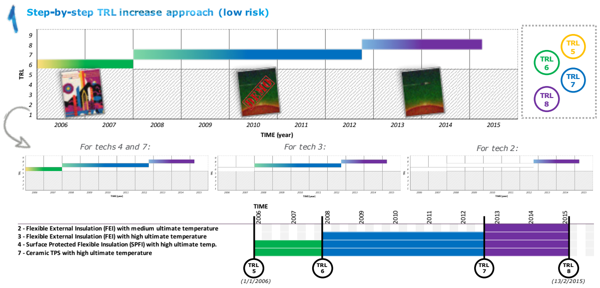


Fig. 9. Pure technical approach: roadmap in three steps, one per each TRL

For the second approach, the more realistic approach, 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.

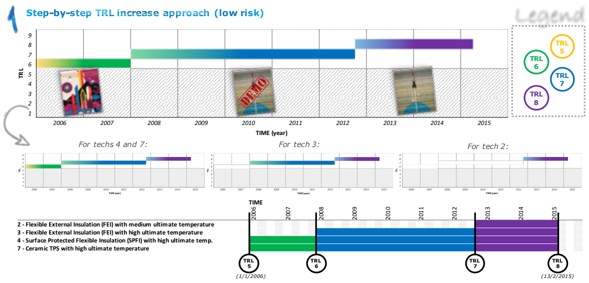
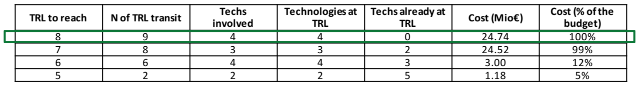


Fig. 10. More realistic approach: roadmap in three steps, one per each TRL

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.

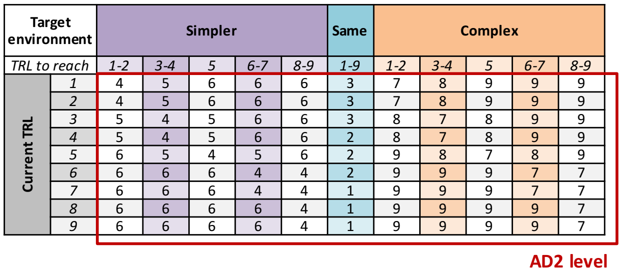
In addition, a preliminary risk analysis has been completed to account for the extra budget that could have been allocated to the project on the basis of the AD2 and the methodology presented in Fig. 7. Thanks to this analysis a total cost increase of about 0.6 Mio€ was estimated, taking into account the AD2 level shown in Table 4. Main results are reported in Table 5.

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%

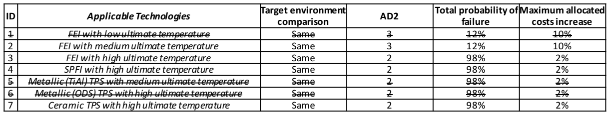
Table 4. AD2 level



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

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%

4. Conclusions

To overcome both the lack of data and of a common and shared vision within the are of hypersonic, re-entry and generally future reusable space transportation systems, the study presents and discuss 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 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, operational capabilities, building blocks or technologies' maturation, correlated with cost and time [17] budgets.

The methodology has been implemented through two software tools: HYDAY 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 tools appear therefore to be reliable and flexible, and potentially useful for users and stakeholders. Users and stakeholders are required to provide inputs to make the tools work properly (see Fig. 11) but are also expected to receive benefits from the tool's outputs in terms of decisions of technologies and missions (programs) prioritization, suggestion of potential (new) mission concepts and BBs and of course technology roadmap generation. In particular, it is worth underlining the crucial role that the suggestion of potential (new) mission concepts and BBs could play in the overall strategic development plans.

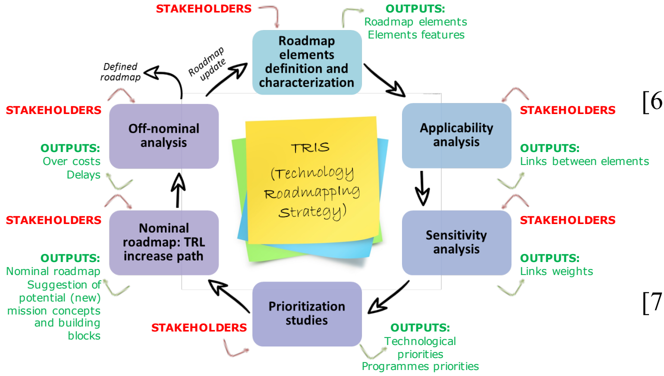


Fig. 11. Expected inputs and outputs of the application of the methodology

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