Design methodologies for space systems in a System of Systems (SoS) architecture

Design methodologies for space systems in a System of Systems (SoS) architecture / CRESTO ALEINA, Sara. - (2020 Jan 13), pp. 1-221.

Publisher:
Politecnico di Torino

Published
DOI:

Doctoral Dissertation
Doctoral Program in Mechanical and Aerospace Engineering (30th Cycle)

Design methodologies for space systems in a System of Systems (SoS) architecture

By

Sara Cresto Aleina

******

Supervisor(s):
Prof. Nicole Viola, Supervisor
Prof. Paolo Maggiore, Co-Supervisor

Doctoral Examination Committee:
Prof. Stéphanie Lizy-Destrez
Prof. Richard Ambrosi
Dr. Victor Fernandez Villace
Prof. Eugenio Brusa
Prof. Sabrina Corpino

Politecnico di Torino
2018

Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Sara Cresto Aleina

2018

* This dissertation is presented in partial fulfilment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

Acknowledgment

I would like to thank all those people who have helped me in the realization of this work with suggestions, criticisms and observations. All the people mentioned or implied on this page have played a fundamental role in the writing of this Doctoral Dissertation and to them my gratitude goes. First, I wish to thank my supervisor Professor Nicole Viola and my co-supervisor Professor Paolo Maggiore, for the help provided, for the support and for giving me the opportunity to study in deep this particular research field.

I would also like to thank all the people who have help me understanding and interpreting my requests, facilitating my research. Above all, I would like to thank Mr Giorgio Saccoccia, for the patience and availability shown in helping me to understand and model current roadmapping approaches, and Dr. José M. A. Longo, for having shared with me his expertise on hypersonic space transportation and re-entry systems, being fundamental in understanding their design and technical management processes.

Finally, I would like to thank all the people that have been involved with this work and the friends who have encouraged me. In particular, I wish to thank the research team of Design and Development of Aerospace Systems and Technologies at the Department of Mechanical and Aerospace Engineering (DIMEAS) of Politecnico di Torino for having adopted, tolerated and assisted me in these years.

Abstract

In the last few years, aerospace systems have become more and more complex. In order to satisfy the stakeholders' needs, the number of functions implemented in a single system is continuously increasing thanks to the progress of technology and the relationship between different elements and disciplines, which concur to its definition, are growing up. System of Systems (SoS) architecture allows analysing complex systems from higher-level point of view, in which two or more systems cooperate just to maintaining their operational and management independence. This cooperation is not only from the technical point of view but involves strategic, political and economic aspects. Moreover, synergy among projects should be preserved in terms of reliability, reusability and technological development planning in order to guarantee an effective process. In this context, the decision-making becomes complex because strong relationships among local and global strategic plans, project objectives, Program Management, Systems Engineering and technology availability shall be defined. To support the decision-making, the technology roadmap process helps managers and engineers in the early phases of a project, providing elements to identify technologies and capabilities, concurrent missions and SoSs architectures and concepts according to strategic plans.

The present thesis deals with the definition of a methodology for technology roadmap derivation and update that allows identifying an optimal solution within a similar scenario, decreasing roadmap time-to-market by proposing it to stakeholders through a semi-automatic process. This methodology is also known as TRIS (*Technology RoadmappIng Strategy*) and supported by an ad-hoc developed toolchain. TRIS is a rational, data-based and normative roadmapping methodology, based on Systems Engineering tools and processes, merged with Decision Analysis and Program Management tools and able to define and manage mission-oriented roadmaps in the context of an ongoing large-scale collaborative programme, describing SoSs. Through the merge of these tools, TRIS takes into account a high number of design parameters maintaining the right equilibrium among all the disciplines involved in the missions.

TRIS first phase is the "*Roadmap elements definition and characterization*", based on a high-level conceptual design process that generates each roadmap element in a modular and organized way, already highlighting reciprocal links. To

suggest viable paths between roadmap elements, it is important to map these links and study their importance. This is the main aim of the "*Applicability Analysis*" phase. Then, a "*Sensitivity Analysis*" follows to weight the reciprocal link importance, to optimize the results obtained based on market and stakeholders' needs and to verify the results. Finally, an analysis is required before defining a planning, the "*Prioritization Studies*" phase. The main purpose of this phase is to rank the elements, in order to give a priority to the viable paths and define a preferable one. All the data collected until now are crucial for the "*Planning definition*" phase, where the roadmap elements are combined to define a nominal planning both in term of missions that have to be performed to reach a certain technological maturity and in term of schedule and resources to match the programmatic requirements. Certainly, having planned a "nominal" roadmap, contingency situations have to be further analysed to verify the results: with "*Results evaluation*" phase, the roadmap can be verified performing sensitivity analyses on the stakeholders' inputs and a draft risk analysis. Finally, once this process is completed, all data need to be updated and (at least periodically) reviewed. This implies that the elements lists have to be integrated with innovative or future solutions, the elements features can change and their maturity increases. This is an iterative and recursive process aimed at outlining an optimized Technology Maturation Plans and at providing it to the final users.

TRIS is flexible and applicable in different SoSs contexts. In this thesis, two case studies are discussed: in particular, 1) a roadmap about Hypersonic Space Transportation and Re-Entry Systems and 2) a roadmap for a Reusable Space Tugs in Earth Vicinity are proposed and sized according to the European and National scenario. These two fields are highly competitive, especially in Europe: the mastering of technologies associated to them is a mandatory requirement for Europe to stay competitive in a very innovative and dynamic environment worldwide, for future human or robotic space exploration.

Contents

1. System Design and Technical Management Processes 1

1.1. Complexity in system design and management 3

1.2. System Design Processes 6

1.2.1. Design process and tools 8

1.2.2. Type of requirements..12

1.3. Technical Management Processes..14

1.3.1. Roadmapping approaches..18

1.3.2. Roadmap elements 27

1.3.3. Roadmap type...33

1.4. Highlights 35

2. Preliminary Study on Roadmapping Methodology 37

2.1. Context and roadmap scenario 38

2.2. Preliminary Activities 40

2.3. Roadmap Development...44

2.3.1. Roadmap Elements Definition and Characterization Process 44

2.3.1.1. TAs Features 44
2.3.1.2. OCs Features 46
2.3.1.3. BBs Features 48
2.3.1.4. MCs Features 49
2.3.1.5. Roadmap Elements Update Process 50

2.3.2. Applicability Analysis...53

2.3.3. Sensitivity Analysis..61

2.3.4. Prioritization Studies 63

2.3.4.1. Technologies prioritization: process...................................... 65
2.3.4.2. Technologies prioritization: real case comparison 69
2.3.4.3. Other roadmap elements prioritization.................................. 73

2.3.5. Planning Definition *75*

2.3.6. Results Evaluation *79*

2.4. Roadmap Visualization and Update 83

2.5. Highlights 84

3. Evolution of Roadmapping Methodology: Technology RoadmappIng Strategy (TRIS) 85

3.1. TRIS Main Features 87

3.2. TRIS: Preliminary Activities 88

3.3. TRIS: Roadmap Development 89

3.3.1. Roadmap Elements Definition and Characterization Process *90*

3.3.2. Applicability Analysis *95*

3.3.3. Sensitivity Analysis *99*

3.3.4. Prioritization Studies *100*

3.3.4.1. Roadmap elements impact on design analysis 100
3.3.4.2. Technologies ranking 104
3.3.4.3. MCs ranking 106

3.3.5. Planning Definition *107*

3.3.6. Results Evaluation *111*

3.3.6.1. Draft Risk Analysis 111
3.3.6.2. Delays and over-costs estimation 112
3.3.6.3. Desired TRL sensitivity analysis 114

3.4. TRIS: Roadmap Visualization and Update 114

3.5. Highlights 118

4. TRIS Application: Hypersonic Space Transportation and Re-Entry Systems 119

4.1. Context and roadmap scenario 120

4.2. TRIS Application: Preliminary Activities 122

4.3. TRIS Application: Roadmap Development 124

4.3.1. Roadmap Elements Definition and Characterization Process .. *124*

4.3.2. Applicability Analysis *132*

4.3.3. Sensitivity Analysis *134*

4.3.4. Prioritization Studies 135

4.3.4.1. Roadmap elements impact on design analysis 135
4.3.4.2. Technologies ranking 139
4.3.4.3. MCs ranking 141

4.3.5. Planning Definition 141

4.3.6. Results Evaluation 144

4.4. TRIS Application: Roadmap Visualization and Update 146

4.5. Highlights 146

5. TRIS Application: Reusable Space Tug in Earth Vicinity.....................149

5.1. Context and roadmap scenario 150

5.2. TRIS Application: Preliminary Activities..153

5.3. TRIS Application: Roadmap Development 157

5.3.1. Roadmap Elements Definition and Characterization Process ..157

5.3.2. Applicability Analysis...160

5.3.3. Sensitivity Analysis...164

5.3.4. Prioritization Studies 164

5.3.4.1. Roadmap elements impact on design analysis 164
5.3.4.2. Technologies ranking 167
5.3.4.3. MCs ranking 167

5.3.5. Planning Definition 169

5.3.6. Results Evaluation...172

5.4. TRIS Application: Roadmap Visualization and Update 174

5.5. Highlights 175

6. Conclusions 177

8. References 175

List of Figures

Figure 3: the Systems Engineering Engine (NASA, 2017). 3

Figure 4: “Technical Management Processes” and “System Design Processes” interactions (NASA, 2017). 3

Figure 5: Typical conceptual design process. 6

Figure 6: Typical conceptual design process. 8

Figure 7: Stakeholder’ Analysis and Mission Analysis influences on the Systems Engineering Engine and example of Stakeholders’ Analysis tools sequence. 9

Figure 8: Functional Analysis and ConOps definition influences on the Systems Engineering Engine and example of tools sequence. 11

Figure 9: Decision Analysis influences on the Systems Engineering Engine and example of tools sequence. 11

Figure 10: Requirements definition process. 14

Figure 11: Program Management influences on the Systems Engineering Engine and example of tools sequence. 15

Figure 12: Qualitative comparison of different life-cycle phasing (Pritchard, 2006). 15

Figure 13: Overview of procedural approached for technology roadmapping (Moehrle, 2013). 20

Figure 12: General TRIZ phases and tools (Domb, 1999). 24

Figure 14: Overview of the methodology and the graphical layout possibilities. 35

Figure 15: Stakeholders’ Grid. 42

Figure 16: Diagram relating Pseudo-TRL, number of technologies required and “required” weight. 47

Figure 17: Diagram relating Pseudo-TRL, percent of technologies at different TRL. 47

Figure 18: Generic scheme of the process followed for BBs definition..............51

Figure 19: OCs' categories. 51

Figure 20: Hypothetical MCs' categories...51

Figure 21: BBs map. 52

Figure 22: MC, BB, TA and OC are all linked between them and different path are possible according to stakeholders' needs. 53

Figure 23: Applicability Analysis between the first level of BBs and TAs. 55

Figure 24: Applicability Analysis between OCs and TAs..................................55

Figure 25: Applicability Analysis between OCs and TAs (in bold type) or Technology Subject (i.e. the second level of TAs)...56

Figure 26: Applicability Analysis between the second level of BBs (the first one is in bold type) and TAs (in bold type) and Technology Subject (i.e. the second level of TAs). 57

Figure 27: Applicability Analysis between the second level of BBs and MCs....58

Figure 28: Applicability Analysis of technologies onto technologies.................59

Figure 29: Example of Functional Analysis. 60

Figure 30: Example of Applicability Analysis of OCs on MCs..........................60

Figure 31: Map of the minimum pseudo-TRL values differences. 62

Figure 32: Map of the maximum pseudo-TRL values differences.......................62

Figure 33: Cost average and TRL costs effectiveness based on (ESA, 2015b). ..67

Figure 34: Sensitivity analysis results. 67

Figure 35: Applicability TA/BB with prioritization. 75

Figure 36: Methodology for roadmap definition and update scheme...................76

Figure 37: Scheme of the case study application. 79

Figure 38: AD2 and TRL relationship scheme. 80

Figure 39: Proposed risk matrix. 81

Figure 40: AD2 analysis results...82

Figure 41: TRIS Main phases. 86

Figure 42: Technology roadmap definition and update methodology toolchain..90

Figure 43: Preliminary activities process overview. 91

Figure 44: Functional Analysis use in methodology for BB, TA, OC and MC derivation and main database settings. 91

Figure 45: ConOps use in the methodology for BB, TA, OC and MC derivation and main database settings. 94

Figure 46: MCs definition process and possible link with Technology Subjects. 94

Figure 47: Product realization processes contribute to the methodology for BB, TA, OC and MC derivation and main database settings. 95

Figure 48: Applicability analyses. 96

Figure 49: Definition of the applicability map labels through a three-valued logic. 97

Figure 50: Technologies incompatibility analysis and new mission concepts proposal. 98

Figure 51: Scheme of the main purposes of the prioritization process. 100

Figure 52: Technologies impact on design evaluation scheme. 102

Figure 53: OCs and BBs impact on design analysis. 104

Figure 54: Prioritization studies generic scheme. 104

Figure 55: Generic scheme of the proposed methodology for technology prioritization. 105

Figure 56: Schedule definition process. 108

Figure 57: Generalized expectations for the CaC distribution between different TRL transits for a space exploration system. 109

Figure 58: Generalized expectations for the CaC distribution between different TRL transits for a hypersonic space transportation and re-entry system. 109

Figure 59: US DoD life-cycle phases and technology maturity according to (Copeland, 2015). 110

Figure 60: Generalized expectations for the timeframe distribution between different TRL transits. 110

Figure 61: AD2 and TRL relationship scheme. 111

Figure 62: Burlton Hexagon (Burlton, 2011) and PEST analysis external factor relationships (Sammut-Bonnici, 2015). 112

Figure 63: GUI developed for roadmap data visualization. 114

Figure 64: Bar graph roadmap visualization example. 115

Figure 65: Radar graph roadmap visualization example. 116

Figure 66: BB-based roadmap example. 117

Figure 67: MC-based roadmap example. 117

Figure 68: Reference Mission Scenario. 123

Figure 69: Functional Tree example. 125

Figure 70: Trade-space elements related to launch and take-off functions with (5.1). 126

Figure 71: Trade-space elements related to launch and take-off functions with (5.2). 126

Figure 72: Trade-space elements related to transfer functions to be used with (5.2). 126

Figure 73: Trade-space elements related to landing functions to be used with (5.2). 127

Figure 74: Trade-space elements related to servicing (i.e. refuelling) functions with (5.2). 127

Figure 75: Trade-space elements related to mission support functions with (5.2). 127

Figure 76: Simplified representation of the trade space for lower level BBs generation for hypersonic space transportation system. 128

Figure 77: Example of Functions/Products Matrix. 129

Figure 78: Legs of the Mission Reference Scenario for operational MCs generation. 130

Figure 79: Mission Phases vs Modes of Operations. 131

Figure 80: Applicability map between technologies and OCs. 133

Figure 81: Applicability map between technologies and BBs. 133

Figure 82: Applicability map between technologies (compatibility analysis). 133

Figure 83: Pseudo-TRL and the most applicable/required over OCs and BBs.. 134

Figure 84: Sensitivity analysis tables. 134

Figure 85: Sensitivity analysis results. 136

Figure 86: Results for the impact on design analysis criteria on refuelling OCs. 137

Figure 87: Results for the impact on design analysis criteria on BBs. 138

Figure 88: Results of the trade-off performed over the OCs definition processes with (5.1) on the left and with (5.2) on the right. 139

Figure 89: Sensitivity analysis results. 140

Figure 90: Required budget weight main influences. 141

Figure 91: Project phases and generalized expectation for the TRL and CaC evolution. 142

Figure 92: Summary of the technologies status at the end of the nominal roadmap. 143

Figure 93: MCs choice with and without MCs required budget estimation. 143

Figure 94: Schedule definition. 144

Figure 95: AD2 analysis for the IXV example. 145

Figure 96: Example of graphical view of the roadmap for TPS related technologies development for the IXV mission, in case of a step-by-step approach for the TRL increase path. 147

Figure 97: Example of graphical view of the roadmap for TPS related technologies development for the IXV mission, in case multiple TRL transit with one MC is allowed. 147

Figure 98: STRONG space tug depiction (Cresto Aleina, 2016d). 149

Figure 1: Space sector global available financial resources distribution in 2014 (American Space Foundation, 2015). 150

Figure 2: Possible missions based on a Space Tug. 151

Figure 99: Nominal electric space tug MC. 155

Figure 100: DRM for the payload retrieval scenario. 155

Figure 101: Options for the refuelling. 156

Figure 102: Lists of the two trade space variables for the OCs. 159

Figure 103: Scheme of the possible mission legs that can be performed in operational and demonstrative missions. 160

Figure 104: Applicability map between technologies and OCs. 161

Figure 105: Applicability map between technologies and BBs. 162

Figure 106: AD2 analysis results. 162

Figure 107: Applicability map between technologies (compatibility analysis). 163

Figure 108: Sensitivity analysis tables. 164

Figure 109: Sensitivity analysis results. 165

Figure 110: Pareto analysis performed over the BBs list. 166

Figure 111: Pareto analysis performed over the OCs list. 166

Figure 112: Sensitivity analysis results. 168

Figure 113: Project phases and generalized expectation for the TRL and CaC evolution. 169

Figure 114: Summary of the technologies status at the end of the nominal roadmap. 170

Figure 115: MCs choice for the TRL increase path. 171

Figure 116: Schedule definition. 172

Figure 117: Simplified example of graphical view of the roadmap in case of a step-by-step approach for the TRL increase path. 174

Figure 118: Toolchain structure. 180

List of Tables

Table 1: ESA, NASA, Eurospace and ISECG roadmapping activities................ 19

Table 2: TRL summary (ECSS Secretariat, 2014)... 29

Table 3: AD2 summary (Cole, 2013)... 30

Table 4: IRL summary (Sauser, 2009)... 31

Table 5: SRL summary (Sauser, 2009)... 32

Table 6: Roadmap graphical layout examples (INCOSE, 2015; Cresto Aleina, 2017a)... 34

Table 7: Criteria examples. 43

Table 8: (ESA, 2015a) and (Viscio, 2014a, 2013a) example of TAs. 45

Table 9: Sub-systems and BBs map.. 49

Table 10: Criteria combinations ranking according to the two evaluation methods. 69

Table 11: ESA prioritization exercise results... 72

Table 12: HERACLES mission data.. 78

Table 13: AD2 and TRL relationship... 80

Table 14: TRL to reach analysis. 82

Table 15: IXV example data (Behrens, 2004). 132

Table 16: Technologies priority and prioritization for the IXV example data. .. 135

Table 17: Example of results for the impact on design analysis criteria on refuelling OCs. 137

Table 18: Results for the impact on design analysis criteria on BBs................ 138

Table 19: Technologies priority and prioritization for the IXV example data. .. 141

Table 20: TRL sensitivity analysis for the IXV example. 144

Table 21: List of considered technologies and their features............................ 158

Table 22: Mission Phases vs Modes of Operations. 160
Table 23: Results for the impact on design analysis criteria on BBs. 166
Table 24: Results for the impact on design analysis criteria on OCs. 167
Table 25: TRL to reach sensitivity analysis. 173

List of Acronyms

- Advancement Degree of Difficulty
  - AD2 29
- AeroSpace and Defence Industries Association of Europe, formerly AECMA
  - ASD 19
- Agenzia Spaziale Italiana
  - ASI 153
- Air Traffic Management
  - ATM 122
- Analytic Hierarchy Process
  - AHP 11
- Atmospheric Re-entry Demonstrator
  - ARD 120
- Attitude Vernier Upper Module
  - AVUM 155
- Building Block
  - BB 27
- Command, Control & Communications
  - C3 10
- Concept of Operations
  - ConOps 7
- Costs at Completion
  - CaC 43
- Department of Defence
  - DoD 15
- Design Reference Mission
  - DRM 10
- Dynamic Object Oriented Requirements System
  - DOORS® 181
- End-to-End
  - E2E 10
- Ente Nazionale per l'Aviazione Civile
  - ENAC 122
- *Entry Descent and Landing*
  - EDL 72
- European Industrial Research Management Association
  - EIRMA 25
- *European Stirling Radiothermal Generator*
  - ESRG 72
- *Extra Vehicular Activity*
  - *EVA* 46
- Failure Mode and Effect Analysis
  - FMEA 10
- Failure Modes, Effects and Criticality Analysis
  - FMECA 11
- ***Flexible External Insulation***
  - ***FEI*** 132
- Functional Flow Block Diagram
  - FFDB 9
- Functional Mock-up Interface
  - FMI 181
- Future European Space Transportation Investigations Programme
  - FESTIP 120
- Future Launchers Preparatory Programme
  - FLPP 121
- Graphical User Interface
  - GUI 114
- Guidance, Navigation and Control
  - GNC 120
- Human Enhanced Robotic Architecture and Capability for Lunar Exploration and Science
  - HERACLES 39
- Hypersonic DATabase
  - HyDAT 123
- Inflatable Re-entry Demonstrator Program
  - IRDT 120
- *Innovation Support Technology*
  - *IST* 21
- In-Situ Resources Utilization
  - ISRU 48
- Integrated Definition for Functional Modelling
  - IDEF0 10
- Integration Readiness Level
  - IRL 29
- Intermediate eXperimental Vehicle
  - IXV 119
- International Space Exploration Coordination Group

  - ISECG........18
- *International Space Station*
  - *ISS* 69
- *Low Earth Orbits*
  - *LEO*........32
- Mars Sample Return
  - MSR........74
- Medium Earth Orbit
  - MEO........154
- Mission Concept
  - MC........27
- *Mission Control Center*
  - MCC........127
- *Mission Support Center*
  - MSC........127
- Model and Simulation
  - M&S........180
- Model Based System Engineering
  - MBSE........180
- Multi-Purpose Crew Vehicle
  - MPCV........74
- National Aeronautics and Space Administration
  - NASA........15
- Operational Capability
  - OC 27
- Product Assurance
  - PA 13
- Product Breakdown Structure
  - PBS........9
- Programme for Reusable In-orbit Demonstrator for Europe
  - PRIDE........152
- Quality Function Deployment
  - QFD........9
- *Rendez-Vous*
  - *RdV*........46
- Research and Development
  - R&D........18
- Sharp Edge Flight Experiment
  - SHEFEX........120
- Single Stage To Orbit
  - SSTO........124
- Space Advanced Project for Excellence in Research and Enterprise
  - SAPERE........152
- Space Assets For Emergencies
  - SAFE........152
- ***Surface Protected Flexible Insulation***
  - ***SPFI***........132
- Swiss Space Systems
  - S3 121
- System of Systems
  - SoS........1
- System Readiness Level
  - SRL........31
- Systems Modeling Language
  - SysML........180
- Systems Technology and Research National Global Operations
  - STRONG........152
- Technical Performance Measure
  - TPM........11
- Technology Area
  - TA 27
- Technology Readiness Level
  - TRL........29
- Technology RoadmappIng Strategy
  - TRIS........26
- Technology Roadmaps for space Exploration
  - TREx........37
- Teoriya Resheniya Izobreatatelskikh Zadatch
  - TRIZ........21
- Thales Alenia Space Italia
  - TASI........153
- Thermal Protection System
  - TPS........45
- Two Stages To Orbit
  - TSTO........124
- United States of America
  - USA........120
- Unmanned Space Vehicles
  - USV........120
- Variable Specific Impulse Magnetoplasma Rocket
  - VASIMR........152
- Vettore Europeo di Generazione Avanzata
  - VEGA........154
- Work Breakdown Structure
  - WBS........14

Chapter 1

System Design and Technical Management Processes

The design of a system is nowadays a complex activity that involves many disciplines, requirements and stakeholders at the same time and this is particularly true in the space market (Fanmuy, 2016). This increase in complexity is directly related to an increase in the market competition that can be seen in the amount of total financial resources applied to the space sector in recent years (American Space Foundation, 2015). Consequently, more severe societal, environmental, financial and operational requirements have to be addressed, placing technology and innovation management at the centre of a decision-making processes aimed at understanding the connections between technological capabilities and goals to reach. In this scenario is even more important to examine a higher level of systems' architecture: the System of Systems (SoS) (Maier, 1998; Luzeaux, 2013). The managing of a SoS means being able to design and coordinate all the independent systems composing it, establishing a set of common objectives and global strategic plans and applying integrated approaches from the very early phases and all over the design process. For these purposes a tool that can simplify the monitoring the current technological maturation and its managing supporting decision makers is the technology roadmap (Garcia, 1970).

In particular, the present thesis deals with the definition and application of a methodology for technology roadmap derivation and update that allows identifying an optimal solution for SoS design process in early design phases according to a current scenario analysis and stakeholders' needs.

According to (NASA, 2017), System Design Process is used to develop and realize the final products and is composed by three sets of common technical processes (Figure 1): "*System Design Processes*", "*Technical Management Processes*" and "*Product Realization Processes*". "*System Design Processes*" are used to define stakeholder expectations and technical requirements, in order to convert them into the correct design solution. This design solution is one of the inputs of the "*Product Realization Processes*" that are used to create, verify and validate it according to the defined requirements. Significant for these two processes are the results achieved in the "*Technical Management Processes*", used to define, manage and update technical plans related to the defined design solution. These three processes are subject of an iterative and recursive cycle able to reach stakeholders' expectations in terms of detail and requirement balance.

Both Technical Management Processes and System Design Processes have to be further analysed to define and manage SoS architectures through the definition of technology roadmaps. While in the first technology roadmaps are usually defined, the second one is strictly related to the roadmap definition (Figure 2). Indeed, the Technical Management Processes must incorporate the results of the System Design Processes, planning for alternative paths and identifying new areas required for development as the architecture is refined. Similarly, this is true also vice versa: the Technical Management Processes have to identify unfeasible or highly critical requirements and provide that information to the System Design Processes.

Finally, Product Realization Processes are related to both System Design Processes and Technical Management Processes. This is also true for other phases of the system/product lifecycle, such as the one related to operations, maintenance and disposal. On one side, it is required to consider these phases and processes until the beginning of design phase in order to ease and optimize design processes. On the other side, it is useless to have a maturation plan for a product or a system, when there is not the possibility to validate, verify or produce it because not all the facilities and tools related to its validation, verification and production are at an adequate level of maturity. Being the main purpose of the study here presented to focus on definition and application of a methodology for the managing of SoS architectures (i.e. defining technology roadmapping methodologies able to deal with an ongoing mission-oriented large-scale collaborative programme describing a SoS), the actual SoS architecture final design is out of topic. For these reason, all the activities, process and tools related to a SoS management from early design phases to the definition of a maturation plan will be analysed deeper, but always remembering requirements and needs for the entire Systems Engineering Engine.

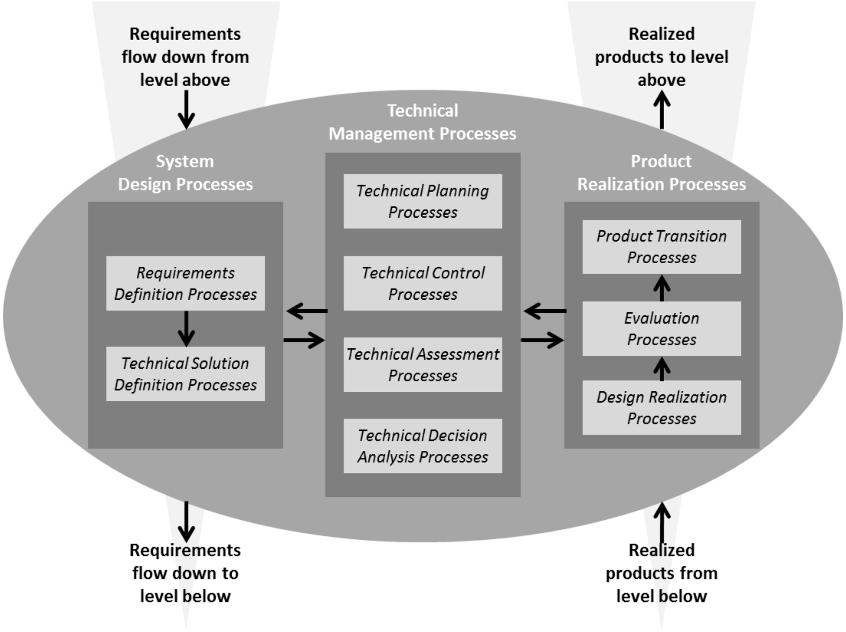


Figure 1: the Systems Engineering Engine (NASA, 2017).

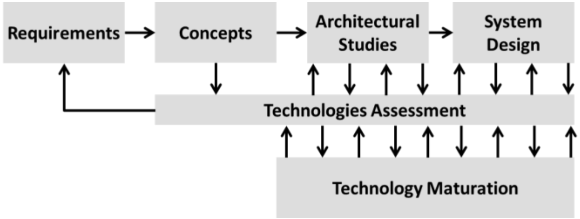


Figure 2: “Technical Management Processes” and “System Design Processes” interactions (NASA, 2017).

1.1. Complexity in system design and management

A system is defined as a product composed by a certain number of elements able to interact between them to accomplish a certain function not achievable by a the single elements alone (Viola, 2012; ECSS Secretariat, 2017; NASA, 2017;

INCOSE, 2015). In literature, SoS are defined differently (Sage, 2001; Hooks, 2004; Luzeaux, 2013), starting from the first definition introduced in (Maier, 1998). It is true, like in the definition of a system, that a SoS is composed by individual systems that, working in the same SoS, perform functions not possible by any of them if operating alone. The peculiarity of a SoS is in different features. First, according to (Maier, 1998) a SoS can be defined as a particular kind of architecture that maintains a certain operational and managerial independence between the different individual systems that compose it, revealing an evolutionary behaviour. In this context, operational independence is defined as the individual systems capability to perform independently from the others, while managerial independence is defined as the individual systems capability to be managed individually, because it has its own purpose that is independent from the other systems. SoS evolutionary development results in the need for a continuous update: it evolves according to new technologies and needs. In addition to these features, individual systems are often distributed over large geographic areas. According to (Kossiakoff, 2011), some additional features have to be included. A SoS is not only usually self-organized, having a dynamic organizational structure that is able to respond to environmental and strategic changes, but also characterized by an high adaptation level being able to dynamically respond to external changes.

Looking the definition criteria, it can be noticed that a SoS is not only related to design activities, but also imply a strong relation with the social, economic and political scenario, balancing all needs and constraint of the stakeholders acting in this scenario. This feature can be seen in the evolutionary development of the SoS and in its self-organization and adaptation capabilities. To design a SoS able to interact in a similar scenario, it is required to balance all the needs and constraint of the stakeholders acting in this specific scenario (i.e. including directly also needs and constraints coming from social, economic and political areas). It has to be remembered that (Larson, 2000) defines the stakeholders as the key players of a mission or a program. It includes sponsors (i.e. the people how pay for it), operators (i.e. the people that control and maintain the system designed once operative), end-users (i.e. the people that receive or use the service produced by the system designed) and customers (i.e. people who pay a fee to use the designed system). In a SoS that deals with the whole social, economic and political scenario, considering the previously listed categories means considering a high number of stakeholders with different even contrasting point of views that have to be considered at the same time in the SoS design. Manage a similar situation, means considering what in literature is called megaproject (Chapman, 2016): megaprojects are project complex to be managed typically for the stakeholders' features or their number (Flyvbjerg, 2016). In addition, megaprojects usually involve high amount of resources and long timeframes. It has to be said that Systems Engineering tools may not be sufficient to manage a similar situation. Activities have to be supported by Program Management theories and tools, that have the objective of finalising a project or a set of projects for which there is a common goal, a finite period of time and dealing with a certain amount of resources (Fanmuy, 2016). In addition, both these two disciplines, needs decision-making processes to achieve the desired result in an effective way. Decision Analysis tools and theories can be applied for this purpose, automatizing also some decisional process (McNamee, 2001). In particular, Decision Analysis is a normative discipline that applies iterative processes and sensitivity analyses to determine data importance or different scenario priorities.

Looking at literature, is therefore, possible to say that a SoS is an architecture composed by a certain number of individual systems that, maintaining their operational and managerial independence and interacting with the external social, economic and political scenario, are still able to accomplish functions not possible by any of them if operating alone. Even if this product seems a complex system, this is not necessarily true: a SoS is not necessarily a complex system, even if it can be composed by a certain number of complex independent systems (Maier, 1998). It has to be said that the definition of “complexity” is subjective and depends on the stakeholders related to the designed product and the current technological situation (Fanmuy, 2016).

Dealing with a complex system, means dealing with a behaviour that cannot be systematically planned or understood: there are “unknowns” in predicting systems behaviour. Indeed, complex systems differ from other systems in their intellectual manageability (Fanmuy, 2016), that implies the impossibility to build or operate them until their behaviour can be considered fully understand, stretching the intellectual limits. The achievement of an effective design for complex systems or projects is necessary related to the managing of the intellectual gap that characterizes them, proposing innovations and managing a feasible way to achieve them. Complexity in systems design needs the definition of a new category of systems: the complex engineered systems, as systems that are so complex that they require Systems Engineering to be correctly designed and managed (Kossiakoff, 2011). Many types of interrelated components compose a complex engineered system and Systems Engineering can ease its study and design. However, this definition is not related necessarily with the definition of the SoS.

Finally, managing a SoS means being able to coordinate the efforts to design, verify and product the individual systems that compose it. This is even more important when dealing with SoS architectures involving a high number of stakeholders, even if supporting its design with Systems Engineering, Program Management and Decision Analysis. A common solution to achieve this is in the definition of a technology roadmap. In particular, exploiting Systems Engineering, Program Management and Decision Analysis main theories and tools to support the definition of a technology roadmap is possible to manage and design a SoS until the early phases of a design activity.

1.2. System Design Processes

Typical "*System Design Processes*" are the conceptual design processes in Systems Engineering (Figure 3). The conceptual design of a generic system is a recursive and iterative process that aims at defining the main requirements that describe it in its features and behaviours, taking into account stakeholders' needs, regulations and other constraints as, for example, from the external environment. This process is iterative and recursive over the different levels of products.

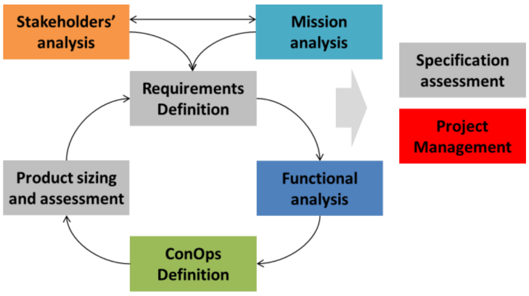


Figure 3: Typical conceptual design process.

Starting from the SoS architecture analysis, it proceeds to the analysis of the individual system that compose it, then to their sub-systems and so on. It has to be remembered that a SoS is defined as an architecture composed by a certain number of individual systems that, maintaining their operational and managerial independence and interacting with the external social, economic and political scenario, are still able to accomplish functions not possible by any of them if operating alone. This means that in analysing the SoS architecture, all the needs coming from stakeholders related to non-technical factors (i.e. political, social and economic factors), have to be transformed in requirements that will affect the design process together with more technical requirements. These requirements together will affect first the individual systems design and then the other products levels of detail. It is true that the Mission and the Stakeholders' Analyses refer to the SoS architecture level and have effects later in the design process, while the other phases pictured in Figure 3 have to be performed in each iteration starting from the results of the phase before (i.e. with a recursive behaviour).

The entire process starts with the definition of the main objectives of the project usually derived directly from Mission and Stakeholders' Analysis (Larson, 2005; Scholes, 1998). Particularly, Primary Mission Objectives and Constraints are derived direct consequence of the Mission Statement, fundamental part of the Mission Analysis. On the contrary, Secondary Mission Objectives and Constraints are derived from Stakeholders' Analysis. In the Stakeholders' Analysis, stakeholders are identified, categorized, analysed and their needs are listed and studied. Many categorizations are possible, such as the one proposed in (Larson, 2000) related to the study purposes and the field of application. In the management of a roadmap describing a SoS, a similar categorization is not complete. First, it does not relate completely with the stakeholders external to the SoS and this group of them in the case of a SoS, by definition, can have a strong influence on the SoS itself. Secondly, it is not easy to relate the stakeholders with their impact and influence on the process. A classification mode related to Program Management can be applied, such as the one proposed in (Kian Manaesh Rad, 2014) that considers both the internal and external scenario of a megaproject. In both cases, the requirements derived from these first two phases are the highest level (i.e. the parents) requirements.

The core of the process is the Functional Analysis, used to find and describe activities to be performed and products able to perform them (NASA, 2017; Viola, 2012; Viscio, 2013d) and to define the main requirements that will drive the system design (Cresto Aleina, 2016d). Functional Analysis is strictly related to the Concept of Operations (ConOps) definition, used to derive how the different products can work together to achieve the Mission Statement (NASA, 2017). In this phase all the aspects of the mission has to be considered, including integration, test, launch and disposal, describing mission phases, modes of operation, mission timeline, operational scenarios, data architecture, operational facilities, integrated logistic support and critical events. Then, system budgets (i.e. mass, power, link, data and Δv budgets) allow sizing the various products in terms of required performance (Lovera, 2016), supporting the product assessment. Finally, it is common to have one or more operational scenarios and architectures that can solve the Mission Statement according to all the requirements: trade-off studies are employed to define the preferred solutions, before increase the design detail (e.g. from system level to sub-system level) or with the definition of the end product requirements, used in the verification phases.

1.2.1. Design process and tools

The main output of a typical conceptual design process is the definition of requirements describing the system architecture compliant with stakeholders' needs, imposed constraints, key drivers and contour conditions, obtained through a systematic (i.e. step-by-step) approach. Particularly, this process can be divided into interconnected sub-phases in which a certain number of data are derived, supporting this derivation with Systems Engineering tools (Figure 4).

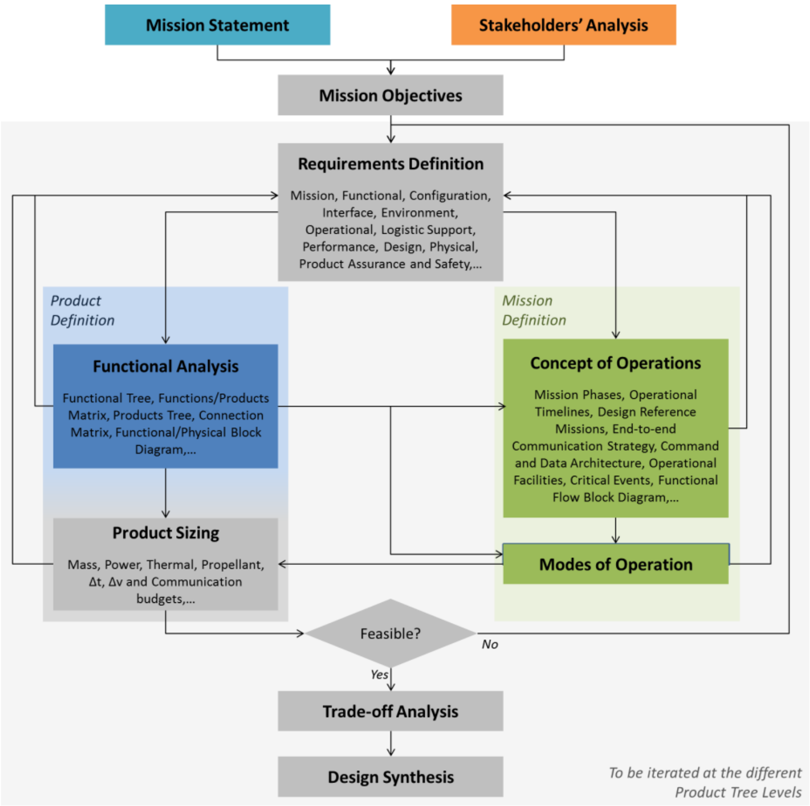


Figure 4: Typical conceptual design process.

While there are not typical tools to support the Mission Analysis, some tools can be employed to analyse stakeholders and their needs. Typical Stakeholders' Analysis tools are the Stakeholders' Matrix (i.e. a matrix describing stakeholders in terms of interest, impact and potential strategies), the Stakeholders' Network Diagram (i.e. a diagram describing stakeholders relationships, such as in (Fiore, 2017)), the Stakeholders' Grid (i.e. a strategy grid categorizing stakeholders' influence and interest in the designed product) and the Quality Function Deployment (i.e. QFD, a Japanese tool able to translate stakeholders' qualitative needs into quantitative needs) (INCOSE, 2015; Patrignani, 2017). All these tools can be used in a logical sequence supporting the Systems Engineering Engine. Each tool application depends on the project objectives and the expected results and, for the same reason, not all of them are required (Figure 5).

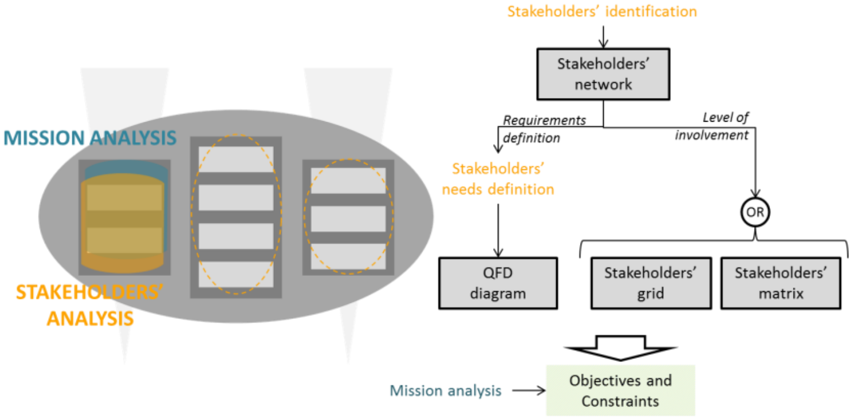


Figure 5: Stakeholder' Analysis and Mission Analysis influences on the Systems Engineering Engine and example of Stakeholders' Analysis tools sequence. *Shaded areas means a primary influence and application of these analyses, while circled areas means a strong influence these analyses results even if not directly applied.*

Many are the tool that can support Functional Analysis. The main one is the Functional Tree (i.e. a diagram defining hierarchically the functions to be performed) (Viola, 2012). Other examples of tools that can be employed are the Functional Flow Block Diagram (i.e. FFDB, that gives further information about timing and functional logical sequences and called "enhanced" if dataflow is described) (Aizier, 2012), the Product Breakdown Structure (i.e. PBS or Products Tree) (NASA, 2017) , the Functions/Products Matrix (i.e. a QFD describing links between products and functions) (Viola, 2012), the Timing diagram (i.e. tool directly related to the Timeline Analysis and its description) (NASA, 2017) , the Entity Relationship Diagram (i.e. a graph describing product entities and their relationships with standard symbols) (Chen, 2002), the Integrated Definition for

Functional Modelling (IDEF0) diagram (i.e. a graph designed to model the decisions, actions and activities of an organization or products with a standard language) (US Government, 2001), the Connectivity Matrix, the Functional/Physical Block Diagram (Viola, 2012) and the N2 Diagram (NASA, 2017) (i.e. diagrams describing links and links type between products). In this list of functional tool, some of them are able to give a logical sequence (e.g. FFDB). Even if tools as FFDBs are able to define better functions features, they are also related to the definition of functions logical sequence. It has to be said that these tools have not a direct relation with the temporal evolution of the scenario (e.g. Mission phases sequence or the Modes of Operations) or with the physical architecture of the design product (e.g. mission architecture or products interfaces). On the contrary, they allow a first draft analysis of these data being an important input for the ConOps definition. For this reason, these types of tools can be considered as partially in the Functional Analysis and partially in the ConOps definition. These tools are a link between Functional Analysis, that has to define functions to be performed, and the ConOps definition, that has the aim of describing mission processes. Other tools of the ConOps definition are (NASA, 2017; Gogolla, 2015): the State Analysis (i.e. diagram describing product states relationships), the State Machine Diagram (i.e. diagram describing processes for different product state changes), the System State Matrix (i.e. matrix describing states links, Mission Phases and Modes of Operations) (Cresto Aleina, 2016d), the Operation Timeline (i.e. tool describing Mission Phases time sequence), the Operational Scenarios and/or Design Reference Mission (DRM) diagram (i.e. diagram describing the actions time sequence focusing on the involved products), the Sequence Diagram, the Activity Diagram (i.e. diagram describing the actions sequence), the Data Flow Diagram, the End-to-End (E2E) Communications Strategy, the Command, Control & Communications (C3) Architecture (Larson, 2000) (i.e. diagrams describing the communication architecture and the data flow), the Context Diagram (i.e. diagram displaying the product in its external environment) and the Use Case Diagram (i.e. diagram describing the product objectives and the link with the stakeholders). As before, these tools can be used in a logical sequence and not all them are required (Figure 6).

The selection of a preferred solution has to be supported by trade studies, which help to complete the selection with more confidence. Decision Analysis is a discipline that can support this phase. Some tools related to Decision Analysis are more related to a Risk informed Decision Analysis such as the Risk Matrix, the Failure Mode and Effect Analysis (FMEA), the Failure Modes, Effects and

Criticality Analysis (FMECA) and the Fault Tree or some of them are more related to trade studies such as the Objectives Hierarchy (also known as Technical Performance Measure, TPM), the Trade Tree, the Influence Diagram, the Decision Tree, the Decision Matrix and the Analytic Hierarchy Process (AHP) (NASA, 2017). Similarly as before, these tools can be used in a sequence together with the previous ones and not all these tools are required (Figure 7).

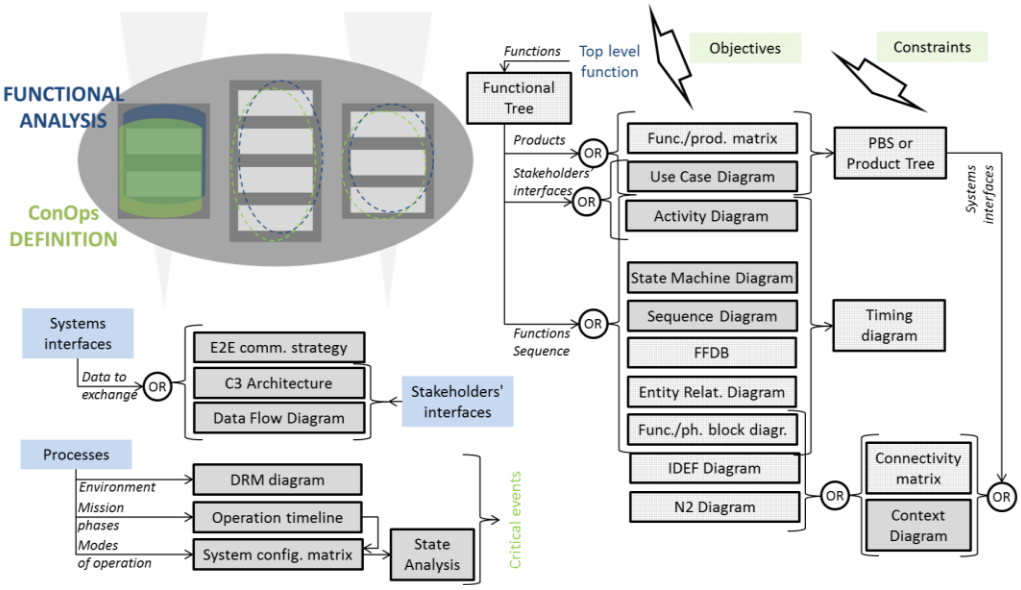


Figure 6: Functional Analysis and ConOps definition influences on the Systems Engineering Engine and example of tools sequence.

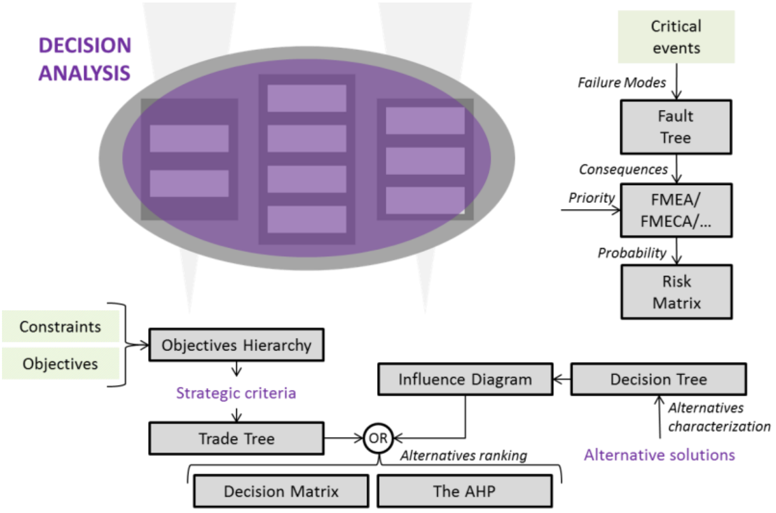


Figure 7: Decision Analysis influences on the Systems Engineering Engine and example of tools sequence.

1.2.2. Type of requirements

Main output of a System Design Process is the requirements list, basis of the whole system design. To support this derivation process and check for eventual lacks, requirements have to be both to be derived in a rational and logical process. This eases also their categorization that is important to reduce repetitions and to assist their verification. Figure 8 shows requirements categories and how they are related between them and with the design phases (NASA, 2017; Larson, 2000).Indeed, even if there is not an agreement with requirements categories, in Aerospace Engineering (NASA, 2017; Cresto Aleina, 2016d) it is usual to define the following requirements that by definition are defined in specific phases of the design process:

- *Mission requirements:* statement related to a task or a function performed by a product that yields a quantifiable and observable result;
- *Programmatic requirements:* statement related to strategic needs, performances, schedule, costs and other nontechnical constraints;
- *Functional requirements*: statements that “define what functions need to be done to accomplish the objectives” both from the mission and from the stakeholders;
- *Performance requirements*: functional requirements that “quantitatively define how well the system needs to perform the functions”;
- *Configuration requirements*: statements related to the composition of the product or its internal organization;
- *Interface requirements:* statements describing the presence and the type of an interconnection “that exist at a common boundary between two or more functions, system elements, configuration items, or systems”;
- *Physical requirements*: statements ensuring physical compatibility different from interface description;
- *Design requirements*: statements related to the imposed design and construction standards to ease product handling or transporting;
- *Environmental requirements:* statements related to environment envelope that the product has to face in its entire during its life-cycle;
- *Operational requirements:* statements describing the system operability, including operational profiles, utilization environment and possible events (e.g. autonomy, control and contingency);
- *Human factor requirements:* statements related to all the human-system interfaces, considering basic human characteristics;

- *(Integrated) logistics support requirements*: statements ensuring an effective and economic support to the product for its entire life-cycle;
- *Product Assurance (PA) requirements*: statements describing activities that has to be covered by the PA.

According to (NASA, 2017) “top-level mission requirements are generated from mission objectives, programmatic constraints, and assumptions” (i.e. mission and programmatic requirements). Finally, it has to be said requirements categories depend from case study and the stakeholders needs. For example, PA requirements can be divided into reliability e safety requirements if needed.

Figure 8 reports a flow chart that highlights the connections between the different tools described before (e.g. Functional Analysis tools and ConOps tools) and categories of requirements. In particular, on the left hand side of the flow-chart there are tools and each tool is useful to derive certain specific categories of requirements. It is worth noting that mission requirements stem out directly from mission objectives, programmatic constraints and assumptions. Functional, configuration and interface requirements derive from the Functional Analysis and respectively from the functional tree and the functions/products matrix, the functions/products matrix and the product tree, and the functional/physical block diagrams. Environmental, operational and logistic support requirements derive from the ConOps and respectively from the mission phases, the FFBDs and the modes of operations together with the mission timeline, and from the mission timeline and the integrated logistic support.

The categories of requirements in the boxes in the center of the flow-chart are those families of requirements which can be defined on the basis of specific tools (“primary” requirements), whereas the requirements in the boxes on the right hand side of the flow-chart are those types (performance, design, physical, product assurance & safety) that cannot be defined on the basis of specific tools but derive from other categories of requirements (“secondary” requirements). For sake of clarity, as an example of primary and secondary requirements, we can think of functional and performance requirements: first functional requirements can be defined or refined on the basis of Functional Analysis, considering the functions that the system shall be able to perform, eventually performance requirements will be established considering how well those functions shall be performed. The arrows in the flow-chart show not only the relationships between primary and secondary requirements but they do also reveal a general sequence of derived categories of requirements. Within primary requirements, first mission requirements can be established, and then functional, configuration, interface, environmental, operational and logistic support requirements can be defined in sequence.

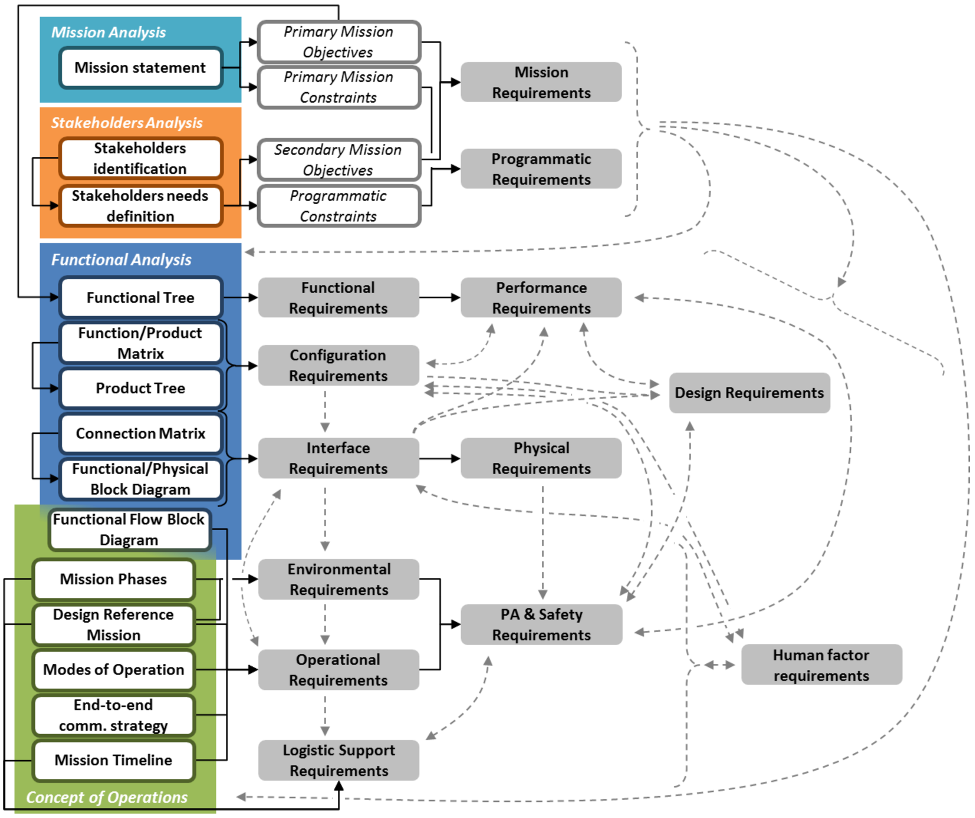


Figure 8: Requirements definition process.

1.3. Technical Management Processes

As previously stated, "*Technical Management Processes*" are used to define, manage and update technical plans related to the defined design solution. This processes category is used not only to plan technology maturation activities at the beginning of a project, but it is a support also in the final project phases to verify performance, configuration and decisions (Figure 9) (NASA, 2017). When dealing with a single project (i.e. a specific design activity), Systems Engineering and Program Management tools can cooperate to define technical plans related to the project life-cycle. Example of Program Management tools are the Work Breakdown Structure (WBS), the Gantt chart and the Workflow Diagrams

(NASA, 2017). Defining Systems Engineering and Program Management processes is usual to refer to project life-cycle phases' subdivisions covering every project phase from the first concept studies to the disposal. Different types of government or commercial life-cycle phasing are available in literature, such as National Aeronautics and Space Administration (NASA), the US Department of Defence (DoD) or ESA life-cycle phasing (NASA, 2005; US DoD, 2017; ECSS Secretariat, 2009). Figure 8 provides a comparison of different life-cycle phasing (NASA, 2005).

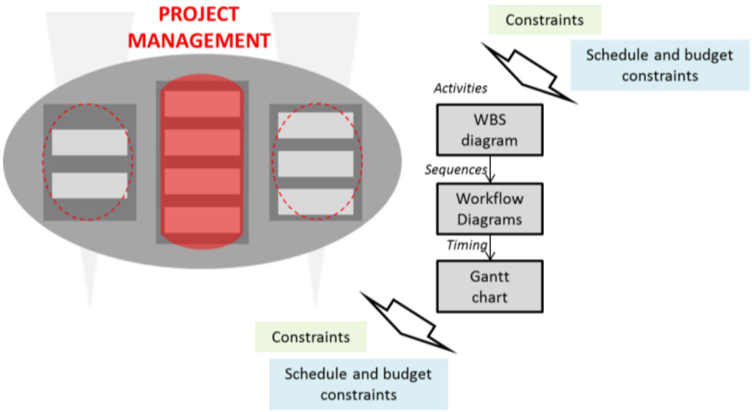


Figure 9: Program Management influences on the Systems Engineering Engine and example of tools sequence.

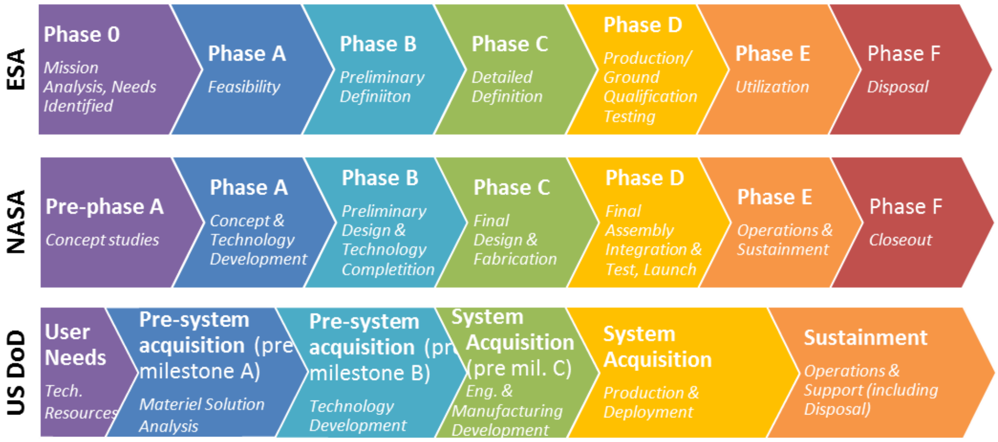


Figure 10: Qualitative comparison of different life-cycle phasing (Pritchard, 2006).

On the contrary, when dealing with a SoS, each different independent system is composed by technologies that can be related to projects that are external to the single design activity under analysis. Define technical plans to achieve a desired maturity level in these technologies means moving between multiple projects and, probably, between different stakeholders (i.e. in a megaproject). To manage correctly Technology Maturation Plans, it is important to consider this entire scenario. Considering the entire scenario and defining a comprehensive plan to coordinate it, means defining a technology roadmap (Carvalho, 2013). The data achieved after the roadmap definition are an important part of the decision support packages also during design phases, including strategic decision and Technology Maturity Plans to product architecture definition. In addition, also in this case, being the starting point the SoS architecture, a “nominal” Technology Maturity Plan that considers only technical factors is not complete. Indeed, a SoS is not only related to design activities, but also implies a strong relation with the social, economic and political scenario. In particular, some external factors that can have an influence on a design process or on a business and can be found also in these non-technical factors that have to be studied and identified (i.e. identifying out of nominal situations).

The process described in the previous sentences is a roadmapping process. A technology roadmap is a summary of science and technology plans, achieved after a current situation analysis aimed at identifying and selecting a certain number of strategic elements according to specific strategic plans and programmatic requirements (Carvalho, 2013). The performed current situation analysis is a technology roadmapping activity (i.e. a planning activity aimed at identifying and forecasting strategic plans regarding a certain scenario) (Cresto Aleina, 2016c). When dealing with SoSs or with megaprojects, a roadmap can ease their management, coordinating the different stakeholders and their specific interests. A roadmapping process has two outputs: the application (i.e. the roadmapping methodology, the applied roadmapping approach) and the result of this application (i.e. the roadmap, the plan and its graphical representation). A roadmapping process is usually composed by three main phases. The first phase includes the preliminary activities that are aimed at defining and analysing stakeholders, research objectives and constraints. Then, it follows the development of the roadmap, in which the main roadmap elements, the critical products or scenario, technology maturity increase paths and timelines have to be defined. Finally, the follow-up activities phase is aimed at improving and updating the previous results. Thanks to this process, it is possible to define and manage a specific path by which it is possible to reach the strategic objectives considering each constraint. Typically, specific path data are (IEA, 2014):

- *Goals* (i.e. desired targets or outcomes);

- *Milestones* (i.e. the interim targets in terms of technology maturity or resources utilization);
- *Gaps and barriers* (i.e. potential constraints in the goals or milestones achievement);
- *Action items* (i.e. actions that allows to overcome gaps);
- *Priorities and timelines* (i.e. a list of the most important actions items and strategies in order to achieve the goals in a certain timeframe).

Defining the goals of the roadmapping activity is an important step, because these goals are important requirements and constraints that can limit the roadmap derivation. Defining a clear statement that describes these goals is like defining a Mission Statement and deriving directly Primary Mission Objectives and Constraints (i.e. the goals) from it. This particular statement is not describing a mission, but it is the envelope of the objectives and constraints of all the projects regarding a specific SoS. For simplicity, this statement can be called Research Study Objective (Cresto Aleina, 2017d).

It is worth remembering that the roadmapping approach depends from the different organizations that are carrying out it and the main strategic interest that the resulting roadmap has to display. Together with strategic interests, programmatic requirements (such as the available budget, milestones and timeframe), SoS and megaproject feature are important inputs. These inputs are the main driver not only for the kind of resulting roadmap but also for the kind of method that has to be applied. For example, considering defining a method able to correctly manage and deal with a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme. In this context, stakeholders from different companies and organizations have to be considered as independent and can have contrasting specific interests that can limit the roadmap efficacy and slow down the entire process. Therefore, a reduced number of workshop and stakeholders' interactions can simplify the roadmapping activity. In addition, a method able to support roadmapping activities in this context usually is not supported by a large amount of data, being these data in many cases classified, and for this reason many roadmapping elements, their features and eventual link between them will have to be supposed.

1.3.1. Roadmapping approaches

One of the very first attempt of technology roadmapping process was provided by Motorola in 1987 (Willyard, 1987) and after this, different methodologies, approaches and examples have been made available in literature (Carvalho, 2013; Doericht, 2013; Farrokhzad, 2013; Fenwick, 2009; Nimmo, 2013). As already stated, even if based on different methodologies the majority of the roadmaps are based on interviews and defined through a manual process that not only can take years, but also leads to subjective data collected and in a difficult data management. As an example, Table 1 compares examples of current roadmapping attempts in the space exploration sector. In particular, the main space exploration roadmapping efforts are (ESA, 2015b; NASA, 2015; ASD-Eurospace, 2012; ISECG, 2018). Looking at these references, it has to be noticed that, even if they represent the same topic sometime in different areas, the roadmaps provided have different features. The main differences that can be noticed are in the basic roadmap elements description, in type of roadmap definition process, in the type of data provided and in the presence of online resources (Table 1). In the type of data provided are included considerations on the adopted roadmapping methodology, on the data provided for the identified technologies (e.g. maturation plan, application, activities and Research and Development (R&D) costs) and on the summary of the overall results.

Currently, almost all roadmaps are based on interviews with stakeholders (such as industries and experts) in a manual process that usually last 2-4 years (ESA, 2015b; NASA, 2015; ASD-Eurospace, 2012; ISECG, 2018; Saccoccia, 2012, 2014). A first problem in applying a similar process is in the subjectivity of the data collected: indeed, involved stakeholders are sometime limited in their single perspective, lacking in an integrated point of view able to include all crucial roadmap elements. A second problem is in the roadmap manual definition and update that can be difficult for the high number of interrelated data and for the continuous evolution of the roadmap elements due to innovation and maturation activities (Kerr, 2013).

It is worth highlighting that the roadmapping approach is different with the different organizations that are carrying out it. For example unlike major space agencies, the definition of the roadmapping process at International Space Exploration Coordination Group (ISECG) is not based on interaction with stakeholders, because ISECG is a forum set up by 14 space agencies to promote coordination between them (ISECG, 2018). Another particular case of roadmap is the one provided by Eurospace, the space group of ASD (AeroSpace and Defence Industries Association of Europe, formerly AECMA). Indeed, while ISECG is interested in providing an overview of the main strategies that will be followed, this association is more interested in the level of technological maturity has been currently achieved and its future trends. In addition to that, Eurospace and space agencies such as the ESA or the NASA provide the reader with a complete graphical data overview for each technology, but only Eurospace and ISECG then perform data analysis, being interested in providing current future strategic trend from data analysis. Together with data, important data that usually are displayed are both the estimate of development costs and a detail of current and future technologies development activities. These data are mainly provided by space agencies and are useful to give an overview on how it is possible to reach the strategic technological milestones and targets. The interests that lay behind a roadmapping activity are the main driver not only for the kind of resulting roadmap but also for the kind of method that has to be applied. According to (Kleine, 2014), the main rule for this phase is the following: "*There is no wrong or right way*". Considering, for example, defining a method able to correctly manage and deal with a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme. In this context, stakeholders from different companies and organizations have to be considered as independent and can have contrasting specific interests that can limit the roadmap efficacy and slow down the entire process. Therefore, a reduced number of workshop and stakeholders' interactions can simplify the roadmapping activity. In addition, in this context, usually a roadmapping activity is not supported by a large amount of data, being they in many cases classified, and for this reason many roadmapping elements, their features and eventual link between them will have to be supposed.

Table 1: ESA, NASA, Eurospace and ISECG roadmapping activities.

Roadmapping Activities	**ESA**	**NASA**	**Eurospace**	**ISECG**
Basic elements description	■	■	■	■
Definition process based on stakeholders interaction	■	■	■	
Explanation of adopted roadmapping methodology	■	■		
Technologies graphical data overview	■	■	■	
Assessment of technologies target application			■	■
Overall graphical result overview	■	■	■	■
Online database access		■		
Estimate of development costs	■	■		
Current and future techs maturation activities provided	■	■		

In literature, different more or less complete procedural approaches exist for roadmapping methodologies, able to support stakeholders. Some examples are provided in Figure 11, proposed in (ISECG, 2018; Kleine, 2014), focusing on quantitative or qualitative procedural approaches applied to derive technology roadmaps. A first categorization of complete procedural approaches is based on roadmapping purposes, dividing them in exploratory and normative approaches. Exploratory approaches are the one in which the current situation is used to derive possible future and unknown scenarios (i.e. a possible set of roadmaps are provided and used as database for decision-making activities) (Beeton, 2013). On the contrary, normative approaches are aimed at planning and foreseeing all the activities required reaching a preferred future scenario. Considering again the previous example (i.e. a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme), explorative methods have to be preferred. The reason behind that is in the possibility to propose in the roadmap the scenario that better solves the different stakeholders' strategies or needs. Indeed, having a limited number of projects to be managed, means having a limited number of main stakeholders to be satisfied and it is relatively easy to define a preferred future scenario. In the case of a SoS, this phase is not simple, due to the number of stakeholders to be involved and their different strategies. Additional sub-categorizations are related with the main roadmap goals in terms of elements to be enhanced (e.g. market-driven, technology-driven and normative-driven approaches).

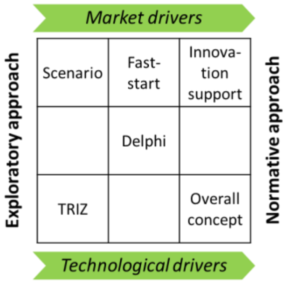


Figure 11: Overview of procedural approached for technology roadmapping (Moehrle, 2013).

In particular, looking at literature (Moehrle, 2013) six type of procedural roadmapping methodologies are explained:

1. *Fast-Start Technology Roadmapping*, based on workshops aimed at supporting innovation and strategies and 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) Technology 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 are more based on technologies requirements to be achieved and other on requirements related to market or business scenarios. 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 (Moehrle, 2013). 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 scenario without proposing a precise one to be reached 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 (Schuh, 2009, 2013) 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 roadmapping process proposed 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 composed 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 (Geschka, 2005, 2013) 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 (Moehrle, 2013). 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 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, for example, by Phaal (Kleine, 2014; Moehrle, 2013; Phaal, 2004), the "*Fast-Start roadmapping workshop approaches*". This approach can have points of view: a technology-driven method also known as "T-Plan" method (i.e. based on product-technology roadmapping) and a market-driven method also known as "S-Plan" method (i.e. based on general strategic challenges at business, corporate, sector and policy levels). The main peculiarity of the methods proposed by Phaal is that are based on interactive workshops between different groups of stakeholders. Another example is the "*Delphi-based Technology Roadmapping*" proposed by Kanama (Kanama, 2010, 2013a, 2013b). Exploiting the Delphi method, even if in an hybrid version that allows technology roadmapping as the result of the process, means exploit panel visions and roadmapping working groups to define sub-roadmap to be integrated in the final roadmap to be proposed. Finally, another example of method highly related to interaction with experts, is the "*IST Technology Roadmapping*" proposed by Abe (Abe, 2009, 2013). 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 remains 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 difficulty 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 overcame 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 by Moehrle (Moehrle, 2005). TRIZ (Kleine, 2014; Moehrle, 2013, 2013) a particular forecasting tool based on a technology-driven approach to study future technological innovations. Even this method is a structured process for technology-driven roadmapping, this method is incomplete for mission-oriented case studies. In addition, even if TRIZ is supported by a tool 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.

In particular, TRIZ is based on the hypothesis that on the basis of innovative ideas there are a short number of principles, called universal principles of invention (Domb, 1999). In particular, coding and identifying these principles, people can learn how to make the process of invention more predictable. The main findings of this basic idea are the following ones:

1. Problems and solutions are repeated across invention processes;
2. Patterns of technical evolution are repeated across invention processes;
3. Innovations use scientific effects outside the field where they were developed.

As a result, TRIZ application consists in learning these repeating patterns of problems, solutions, technical evolution, and methods of using scientific effects, in order to apply them to predict new invention process (Figure 12).

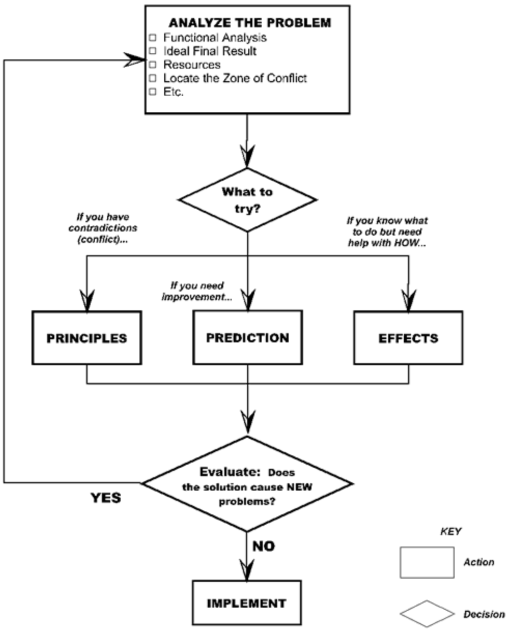


Figure 12: General TRIZ phases and tools (Domb, 1999).

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 (Viscio, 2014). The proposed 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 (Viscio, 2014a, 2013a, 2012). 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 (NASA, 2015), a public NASA tool, and TREx (Saccoccia, 2017), a tool developed by ESA. Both of them allow the location of data information 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 (Viscio, 2014) 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 input coming both from technologies and from business processes. The *European Industrial Research Management Association* (EIRMA) (EIRMA, 1997) 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 it has been 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 feature 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 workshop 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 is possible to simplify also the roadmapping process itself, generating rational draft result to be reviewed or easing the update process because 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 chapter able to generate and update roadmap on the basis of a typical Systems Engineering Conceptual Design approach (Cresto Aleina, 2016d) and exploiting an iterative and recursive multi-steps procedure that is based on NASA and ESA guidelines for the design of complex systems (ECSS Secretariat, 2017; NASA, 2017).

As a result, taking inspiration from all these processes and remembering the main purposes of this research activity, a rational methodology has been studied, optimized and applied at Politecnico di Torino with the main aim of supporting technology roadmaps definition and management in the context of a mission-oriented large-scale cooperative programme (i.e. a SoS described through megaprojects in a space exploration context), reducing roadmap time-to-market.

Main references for this methodology are Systems Engineering, Decision Analysis and Program Management theories and tools (Viola, 2012; Cresto Aleina, 2016d, 2016a; Stesina, 2017). Indeed, exploiting Systems Engineering, Decision Analysis and Program Management is possible to propose a draft roadmap to experts for review, without having the need of supporting the draft roadmap definition with experts' opinions as is currently done. In this way, experts will have to review a roadmap obtained based on modular and structured elements obtained exploiting, in particular, Systems Engineering theories. This modularity itself is able to make the methodology flexible to different types of applications and stakeholders, aiming also at creating in a semi-automatic process able to support the roadmap definition, substituting stakeholders' interactions when not strictly required. As a result, this methodology is able to start from the roadmap elements definition and characterization and proceeds up to the definition of a planning in terms of budget, schedule, missions and out-of-nominal situations analysis, taking into account the current scenario and a certain number of programmatic and strategic constraints coming from stakeholders. This methodology has been called TRIS (Technology RoadmappIng Strategy).

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 (Bilbro, 2006).

1.3.2. Roadmap elements

Even if different approaches can be applied in defining or updating a roadmap, all of them have to face with a database of elements that are a reference in the specific application field. Considering space exploration context, the major agencies and stakeholders actually defining technology roadmaps (such as (ESA, 2015b; NASA, 2015)), usually refers to four groups of elements:

- *Operational Capability* (OC), i.e. a high level performance requirement able to achieve the Research Study Objective;
- *Technology Area* (TA), i.e. a set of technologies, defining them as the result of the use of science and engineering based knowledge to meet one or more OCs (i.e. BBs sub-systems);
- *Building Block* (BB), i.e. an individual system composed by technologies that is part and is able to operate in the SoS under analysis;
- *Mission Concept* (MC), i.e. an event exploiting BBs and able to achieve a Mission Statement, included inside the Research Study Objective.

Looking at these elements and their definitions is easy to understand that they have to be interrelated. Indeed, if OCs are defined as high performance requirements, they are strictly related to functions defined through the Functional Tree. These functions are linked to the Products Tree through the Functions/Products Matrix. Different levels of the Products Tree, are able, for example, to describe systems, sub-systems and technologies related to the SoS under analysis. Having defined BBs as the systems and TAs as the sub-systems, the Products Tree represents the link not only between OCs and products (i.e. BBs and TAs), but also the link between BBs and TAs. Finally, MCs can be characterized thank to the ConOps definition. In particular, defining the Modes of Operations active in the MCs, it is possible to define the technologies that can be potentially applied in each MC (if not known) considering that each Mode of Operations is defined with a set of technologies (or products) active or not.

It is possible to exploit this interrelation to ease roadmapping activities based on the same theories and tools that are the basis of the System Design Processes. In addition, it has to be said that it is usual in performing a planning to refer not only to a specific Research Study Objective, but also to have it directly related to one or more roadmap elements of strategic importance. In particular, it can be said that an element can "pull" or "push" the roadmapping process (Héder, 2017). If the strategy of the roadmapping process is, for example, technology-push, the target of the process is to enhance a certain known technology without knowing exactly what will be achieved at the end of the process (i.e. knowing the starting point of the process, but not the ending one). On the contrary, a technology-pull strategy start from a precise idea of what has to be achieved and the roadmapping process has to suppose how to achieve this result (i.e. knowing the ending point of the process, but not the starting one).

OCs are important elements to define strategic functionalities and performances that have to or will be achieved, thanks to what has been planned. Looking at the OCs definition, they can be derived selecting areas of high importance that have an influence on the development of technologies. In space exploration past roadmaps, this element was considered at the centre of the planning activity, focusing on the abilities that was required to achieve a strategic target. An example is NASA first roadmapping attempt (Committee on Human Spaceflight, 2014; NASA, 2012) in which OC-based roadmap is provided deriving the technologies that contribute to each OC enhancing. Despite this, listing OCs is still important not only to have a clear view of the abilities required achieving the current strategies and targets, but also to drive technological innovation supporting decision makers in defining what influence a decision can have on agency or company abilities. To size the element influence over the final roadmap or to verify its actual enhancement, it is important to define a quantifiable index or able to describe its status. This index has to be related to the specific OC features and has to relate it with the other roadmap elements.

Hypothesis for this index will be summarized in the next chapter and an index will be proposed.

Current space exploration roadmaps are based on a different type of element: technologies. In literature there are many definitions of "technology" (Floyd, 1997; Whipp, 1991; Steele, 1989), but the proposed one summarize the acknowledged key features of a technology. A technology is different from general knowledge types that can be applied, focusing on the "know-how" of the organisation. Usually, technologies are categorized based on current systems structure, i.e. defining the common sub-systems (or TAs) and the common types of equipment that can compose them (or Technology Subjects). In addition, current system structure is derived starting from the main current and future research areas delivering a tangible and feasible innovation. When looking at a technology-based roadmap, enhancements in this innovation maturity can be quantified by means of Technology Readiness Level (TRL). TRL (Table 2) is a nine-level metric able to categorize and size a specific technology maturity and is an important index if considering technologies role in evolving and innovating the current scenario. being related to technologies evolution, it is useful to size each technology experimentations, refinements and increasingly validating tests.

Table 2: TRL summary (ECSS Secretariat, 2014).

TRL	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard functional verification in laboratory environment
5	Component and/or breadboard critical function verification in a relevant environment
6	Model demonstrating the critical functions of the element in a relevant environment
7	Model demonstrating the element performance for the operational environment
8	Actual system completed and accepted for flight ("flight qualified")
9	Actual system "flight proven" through successful mission operations

In addition to TRLs, other readiness indexes can be considered to quantify other other aspects of each technology status. Indeed, the TRL clearly defines only the degree of maturity of a specific technology at any given point in time and, for every every other features of the same technology, different indexes or parameters have to to be used. For example, Advancement Degree of Difficulty (AD2) (Bilbro, 2006) and and Integration Readiness Level (IRL) (Sauser, 2009) are two types of nine-level metrics that can be applied to define its implementation risk in a mission and its integration capability with other technologies respectively. AD2 (Table 3) sizes the efforts to apply a technology in a mission with new design objectives and it is related

to the risks and consequences on the design of this application. On the contrary, the IRL (

Table 4) measures of the level of maturity of the integration capability between two different technologies even if they are under-development. The study of interfaces and integration activities is critical especially for a SoS, where individual and independent systems have to cooperate between them in a safe and effective way. It has to be remembered that the purpose of this study I not the actual design of a SoS, but the definition of how it can reach a desired level of maturity. For this reason, a study on how to integrate different technologies within the same BBs and in the same MCs has to be performed, even if without actually propose interface requirements or integration procedures. This is possible thanks to IRL definition. Nevertheless, IRL and its study can provide a draft analysis of each technology integration capability and high-level interface requirements.

Table 3: AD2 summary (Cole, 2013).

AD2	Definition	Risk
1	Exists with no or only minor modifications being required. A single development approach is adequate.	<10%
2	Exists but requires major modifications. A single development approach is adequate.	<20%
3	Requires new development well within the experience base. A single development approach is adequate	<30%
4	Requires new development but similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high degree of confidence for success.	<40%
5	Requires new development but similarity to existing experience is sufficient to warrant comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success.	<50%
6	Requires new development but similarity to existing experience is sufficient to warrant comparison on only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. (Desired perf. can be achieved in subsequent block upgrades with high confidence).	<70%
7	Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Multiple development routes must be pursued.	<80%
8	Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be pursued.	<90%
9	Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined	≤ 100%

Table 4: IRL summary (Sauser, 2009).

IRL	Definition
1	An Interface between technologies has been identified with sufficient detail to allow characterization of the relationship.
2	There is some level of specificity to characterize the Interaction (i.e. ability to influence) between technologies through their interface.
3	There is compatibility (i.e. common language) between technologies to orderly and efficiently integrate and interact.
4	There is sufficient detail in the quality and assurance of the integration between techs.
5	There is sufficient control between technologies necessary to establish, manage, and terminate the integration.
6	The integrating techs can accept, translate and structure info. for its intended application.
7	The integration of techs has been verified and validated with sufficient detail to be actionable.
8	Actual integration completed and mission qualified through test and demonstration, in the system environment.
9	Integration is mission proven through successful mission operations.

While technologies are related to the basic level components of the SoS, BBs are the individual systems that compose the SoS. BBs have to exploit the concept of “modularity”, in order to generalize them to the same level of detail. This concept eases also BBs study, driving not only their definition, but also the study of possible links between them and the technologies. Indeed, if BBs are the systems that compose the SoS, it is possible to split them into sub-systems (i.e. TAs) and then to the lower level products (i.e. Technology Subjects and Technologies) that compose them. In order to size the BBs maturity a particular type of index can be employed: System Readiness Level (SRL). SRL (Table 5) is a normalized five-level metric able to describe system maturity, starting from the assessment of the technologies that compose it (i.e. defining each technology TRL and IRL and analysing how the system is organized). Unfortunately, in literature an acknowledged method to define SRL does not exist (Kujawski, 2013). Hypothesis for this index definition will be proposed in the next chapter based on literature analysis.

BBs are able to cooperate in specific events or missions (i.e. MC). These MCs have to be defined in the roadmap starting from past missions, tracking present ones and trying to forecast future ones. MCs can be categorized in different ways, according to stakeholders needs. For example, is different if MCs are categorized according to advancement and funding, target environments or mission objectives (Cresto Aleina, 2015b, 2016c). For example, considering MCs advancement and funding it is possible to define the following categories:

1. *Approved missions* (i.e. missions described by a fixed and not modifiable list of BBs and technologies);
2. *Under approval missions* (i.e. missions described by a partially fixed list of BBs and that are not yet approved);
3. *Potential missions* (i.e. likely missions described by a fully changeable list of BBs and that are still feasibility studies).

Table 5: SRL summary (Sauser, 2009).

Level	SRL	US DoD phase	Definition
≤1.00	1	Materiel Solution Analysis	Refine initial concept. develop system/technology development strategy
≤0.89	2	Technology Development	Reduce technology risks and determine appropriate set of technologies to integrate into a full system.
≤0.79	3	Engineering & Manufacturing Development	Develop a system or increment of capability; reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for production capability; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety, and utility
≤0.59	4	Production & Deployment	Achieve OC that satisfies mission needs.
≤0.39	5	Operations & Support	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manor over its total life-cycle.

While the first category is influent only on the current technological maturity assessment and the third category can only be considered in forecasting future trends, the second category can be considered for both the purposes. Finally, the third category can be divided further into:

1. *Technology maturation activities* (i.e. activities directly related to the enhancements of technologies with low TRL) (INCOSE, 2015);
2. *Potential future concept studies* (i.e. missions in line with the main market objectives and expectations).

While the first sub-category can be related to TRL definitions, the second one has to be suggested starting from market and stakeholders' needs analysis. These sub-categories affect also a different MCs categorization, based on the strategic target environments (or application field). For example, in (ESA, 2015b), three defined strategic target environments are *Low Earth Orbits (LEO)*, *Moon* and *Mars*. In considering Technology maturation activities, from the point of view of mission objectives, MCs can be classified as:

- *Operational missions* (i.e. missions that have been planned to reach scientific and/or technological objectives);

- *Demonstrative (demo) missions* (i.e. missions that have been planned specifically to increase the TRLs of components/ sub-systems/ system).

It is worth noting that the distinction between operational and demo missions can sometimes be tough, as rarely in this field missions can be defined totally operational or demo. For this reason, an index taking into account this feature can be considered, in order to track the mission maturity. Hypothesis for this parameter will be proposed in the next chapter.

1.3.3. Roadmap type

Once defined the roadmapping approach, the elements involved, it is worth remembering that, being the roadmap defined as a map describing all the strategic planning related to a specific scenario, it is important to define its graphical layout. In literature are discussed many different layout types (see Table 6 for a brief overview), according to different company or agency needs and different scenarios. Indeed, stakeholders' needs analysis is an important input for the roadmap type definition, considering that the final roadmap has to be sized to final user needs. In addition, it is important to define the graphical layout of the roadmap also considering that, once the elements are defined, a database collecting all the data that will have to be analysed and displayed in the final roadmap: the graphical layout and the data collection are strictly related. According to literature (UNIDO, 2005), roadmap graphical layout can be categorized as it follows (Figure 13):

- *Bars diagram*, usually describing the TRL increase path for a specific Technology (or a Technology Subject or TA) and the relationship with other groups of elements;
- *Tables*, usually describing time vs. performance in situations where performance can be quantified in specific time periods;
- *X-Y Graph*, usually describing the TRL increase path according to a performance in different curves according to the milestones;
- *Pictorial representations*, usually describing the data in a creative way also exploiting metaphors.

Table 6: Roadmap graphical layout examples (INCOSE, 2015; Cresto Aleina, 2017a).

Tool	Description and Example
3 Horizons model	Tool structured to show time and uncertainty.
Technology trend capitalization	Tool used to discuss current and future market positioning along relevant trends.
Product Canvas	Tool used to communicate the key facts of a product in a single slide to align everyone to the focus.
Technology theme Investments	Tool used to discover areas requiring more resource investments and areas to divest.
Pictures of the future	Tool used to align short-term and long-term vision and brainstorm new opportunities.
Market/technology alignment	Tool used to align marketing messages with technology innovations.
Kano model	Tool used to understand product qualities and their impact on customer.
Compact QFD	Prioritization tool that focuses on customer needs and product qualities relative to competitive products.
Technology S-curve	Tool used to show incremental improvements vs. potentially disruptive technologies.
The golden feature	Tool used to create a singular focus on doing one great thing.
TPM	Tool used to monitor certain attributes to determine how well the product is satisfying a technical requirement or goal.

Another type of categorization is related to the purpose of the technology roadmap, underlining the main strategy that has driven the roadmapping process. Indeed, it is possible to relate with (UNIDO, 2005; Moehrle, 2013):

1. *Product planning*, where the main focus is on linking the technologies on the different BBs;
2. *Service capability planning*, where main focus is on the link between technologies and OCs defining technologies impact on business;
3. *Strategic planning*, where the main focus is on the evaluation of different opportunities typically at the business level, forecasting the future trends and identifying gaps with the current scenario;
4. *Long-range planning*, where the main focus is on extending the planning time horizon, usually in a limited context (e.g. sector or national level);
5. *Knowledge asset planning*, where the main focus is on aligning knowledge assets and knowledge management initiatives with business strategies;
6. *Programme planning*, where the main focus is on the link between technology development, current programme phases and milestones;
7. *Process planning*, where the main focus is on the knowledge flows that are required to ease a new product development and introduction,

incorporating both technical and commercial perspectives;

8. *Integration planning*, where the focus is on the link between different technologies and BBs or new technologies, showing technologies integration process.

If EIRMA approach is proposed, as in the case of a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme, a bar diagram is easier to be implemented without reducing roadmap impact on users. Bar diagrams are also frequent in space exploration context (ESA, 2015b), while frequent are also strategic (LEAG, 2016) and knowledge asset (NASA, 2015) planning roadmaps.

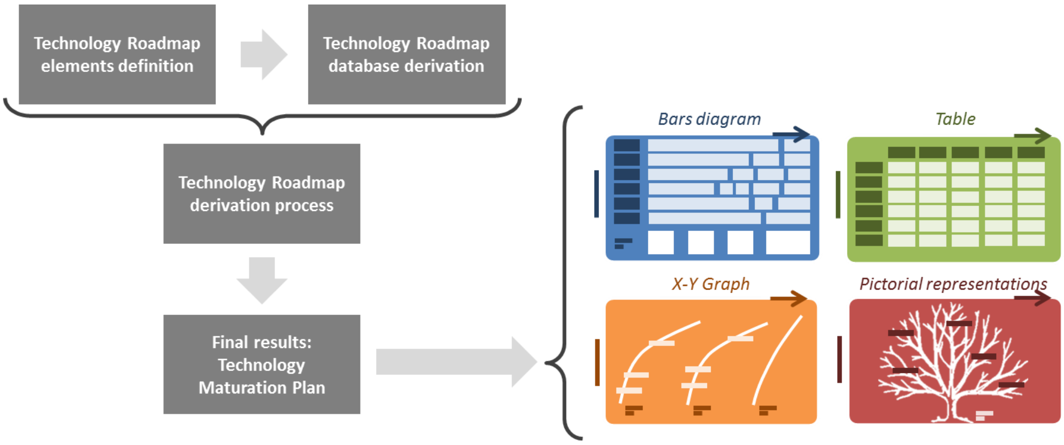


Figure 13: Overview of the methodology and the graphical layout possibilities.

1.4. Highlights

- ✓ A SoS has been defined as an architecture composed by a certain number of individual systems that, maintaining their operational and managerial independence and interacting with the external social, economic and political scenario, are still able to accomplish functions not possible by any of them if operating alone;
- ✓ Manage a similar situation, means considering what in literature is called megaproject: megaprojects are project complex to be managed typically for the stakeholders' features or their number;
- ✓ The design and management of a similar architecture needs Systems Engineering, Program Management and Decision Analysis to support the technology roadmap definition until the early phases of a design activity;

- ✓ A technology roadmap is a summary of science and technology plans, achieved after a current situation analysis aimed at identifying and selecting a certain number of strategic elements according to specific strategic plans and programmatic requirement;
- ✓ A rational methodology has been developed with the main aim of supporting technology roadmaps definition and management in the context of a mission-oriented large-scale cooperative programme, reducing roadmap time-to-market: TRIS;
- ✓ Typical "*System Design Processes*" are recursive and iterative processes that aims at defining the main requirements that describe it in its features and behaviours, taking into account stakeholders' needs, regulations and other constraints as, for example, from the external environment;
- ✓ The "*Technical Management Processes*" are used to define, manage and update technical plans related to the defined design solution (i.e. planning of technology maturation activities, support to performances verification, system configuration and decisions making);
- ✓ The "*System Design Processes*" and the "*Technical Management Processes*" are strictly interrelated: the process of defining a roadmap (i.e. an activity inside the "*Technical Management Processes*") has to deal with "*System Design Processes*";
- ✓ 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, 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;
- ✓ Typical roadmapping activities in space exploration contexts deals with technologies, MCs, OCs and BBs, that are interrelated through Systems Engineering theories and tools;
- ✓ EIRMA approach through a bar diagram is proposed in the case of a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme, reducing roadmap definition impact on users.

Chapter 2

Preliminary Study on Roadmapping Methodology

In order to drive the generation and the update of technological roadmaps a methodology can be proposed based on Systems Engineering, Program Management and Decision Analysis theories and tools to a generic SoS architecture with a mission-oriented approach. As it has been said before, considering the example of a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme, a method can be defined also starting from what is present in literature as approaches and common strategies. This method has been called TRIS.

TRIS has to be flexible enough to adapt to different domains related to SoSs design activities, being applicable to many case studies easing its development and verification. Firstly, using examples in the European space exploration scenario, studies will be proposed to size every methodology phase and their results according to the SoS architecture features. In particular, considering ESA Space Exploration Technology Roadmaps as a database (ESA, 2015b), an update of an existing roadmap will be explored changing priorities in the different roadmap elements and looking at the entire roadmap behaviour. In addition, a Moon initiative, TREx (Technology Roadmaps for space Exploration) features and ESA Space Exploration Technology Roadmaps update process will be analysed. Based on this phase the different steps of the methodology to define and update technology roadmaps will be verified. Then, having defined and sized the main methodology features, an evolved methodology can be proposed and then considered for some applications.

Then, having defined and sized the main methodology features, two examples of complete application are proposed: Hypersonic Space Transportation and Re-Entry Systems and Reusable Space Tugs in Earth Vicinity. The first example is proposed as a real case to be compared with TRIS results, being present in literature more data about Hypersonic Space Transportation and Re-Entry Systems. The main purpose of the second example about a Space Tug is to apply the proposed methodology (TRIS) with minimum guidelines, and check if the final results are realistic or not.

2.1. Context and roadmap scenario

Examples related to the European space exploration scenario will be proposed in order to size and verify the proposed roadmapping methodology, looking at technologies, capabilities, building blocks or programmes that are significant for the current strategies and looking at the way to enhance them.

The European space exploration scenario is an example of a scenario in the context of mission-oriented large-scale cooperative programmes. Indeed, a certain number of programmes and activities are present and these are usually mission-oriented, for the typical System Design Process applied. In addition, for the type of founding and schedule usually involved, these programmes and activities usually involve a large number of stakeholders, requiring the ability in coordinating the different efforts making them cooperate. Again for the amount of budget and time that usually similar contexts involve, it is typical to find political, social and economic necessities or impositions that can compromise the success of entire programs (see (Russel, 2005) for an example). Finally, looking at the technology roadmapping activities in this field (ESA, 2015b; NASA, 2015; ASD-Eurospace, 2012; ISECG, 2018), a common strategic goal can be found. Indeed, it is common to consider Mars human exploration as the main goal of all the stakeholders involved in this field. Remembering the definition of SoS, this specific context is composed by a certain number of programs aimed at reaching a high-level of maturity in all the individual systems that, if coordinated in a common mission or SoS architecture, can enable a future human Mars exploration programme.

The main references are the ESA Space Exploration technology roadmaps (ESA, 2015b). (ESA, 2015b) have been developed by ESA in cooperation with the different ESA stakeholders (e.g. European Industries and Research Institutes) from 2011, with the main aim of providing a powerful tool for strategic, programmatic and technical decisions in support of the European role within an International space exploration context. The latest edition has been released in 2015, giving an overview of the status and the future developments required to obtain the right maturity in a large database of technologies, programmes and technology maturation activities. This database is currently implemented in a tool able to track technology maturity and progresses, TREx (Saccoccia, 2017). Even if an update process has been carried out to increase data confidence and update it, TREx is highly related to the ESA Directorates in the technologies list, in the confidence on the provided data and in the list of activities, even if inputs external to ESA are collected and considered. This last feature is also the main database limit, resulting, in a limited flexibility in adding or modifying roadmap elements that are constrained to ESA internal structure. Despite this, TREx is an important database collecting a large amount of data and can be useful to verify the proposed roadmapping methodology phases.

In addition, a specific programme has been considered in this phase. Looking at current strategies, Moon exploration initiatives are currently considered as an important step to expand human space exploration and to achieve important scientific outcomes (LEAG, 2016; ISECG, 2018). In this context, since 2015, ESA was supporting a specific lunar mission concept for robotic samples return in the timeframe 2020 to 2030: Human Enhanced Robotic Architecture and Capability for Lunar Exploration and Science (HERACLES) (Hufenbach, 2015). HERACLES is a particular kind of preparative mission that focuses on returning samples from the Moon and expanding human presence to this destination, foreseeing the possibility to expand it to Mars in a step-wise approach. In particular, this final mission was composed by multiple robotic missions on the lunar surface, to prepare a future human space exploration. HERACLES mission is important not only for its specific objectives, but also because it includes all the important building blocks and capabilities required for a lunar outpost even if in a simplified context if compared to a Moon Village.

2.2. Preliminary Activities

In defining a roadmap every process starts with a certain number of preliminary activities that have the main purpose of defining scope and boundaries for planning in order to guarantee the satisfaction of the essential conditions (Garcia, 1970). If this phase is performed following the typical System Design Process, defining scope and boundaries means defining Mission Statement, mission objectives and constraints. Defining these data, means having a clear view of the current scenario in terms of market possibilities, current state of the art and design and mission constraints starting from the market and stakeholder' needs analysis. Imagine following a typical System Design Process also in defining a roadmap: this can ease the definition of the main roadmap features also considering the use of a logic process that is common in space exploration System Design Processes and that can be easily understood by experts in this field. In addition, this can ease also the System Design itself, having every data structured through the same logic process.

In the same way in which the Mission Statement is derived, it is possible to derive the Research Study Objective. The Research Study Objective is related to a reference or strategic mission when required by the stakeholders. For example, in considering a change of priority in a MC, all the roadmap has to be updated in order to support this change of priority. In this particular case, the Research Study Objective has to be related to this reference MCs. An example is the change of priority of a particular moon exploration mission (i.e. HERACLES) (Cresto Aleina, 2017f):

> "*To design and manage a SoS able to perform multiple robotic lunar surface exploration missions aimed at returning samples from the Moon and expanding human presence to these destinations in a step-wise approach.*"

Differently, an example referring to a roadmap definition and not a partial update can be found in the Global Exploration Roadmaps of 2013 (ISECG, 2013):

> "*The Global Exploration Roadmap highlights the efforts of agencies participating in the ISECG to prepare for human and robotic exploration of destinations where humans may someday live and work.*"

Every Research Study Objective has to refer to the main roadmap approach, the main strategies or constraints (such as reference elements or scenario). Contemporary, an analysis of the main stakeholders involved in the roadmap scenario has to be performed. As in a common System Design Process, stakeholders have to be categorized, analysed defining mutual relationships and their influence or interest in the process results. In space exploration System Design Processes it is common to categorize the stakeholders according to their role in the process (Larson, 2000). In the management of a roadmap describing a SoS inside a megaproject, a similar categorization is not complete. First, it does not relate completely with the stakeholders external to the SoS and this group of them in the case of a SoS, by definition, can have a strong influence on the SoS itself. Secondly, it is not easy to relate the stakeholders with their impact and influence on the process. Indeed, according to (Chapman, 2016), a megaproject (and so a SoS) has to relate with a certain number of "extremal complexity indicators", related to the megaproject features. In a megaproject, the main source of complexity is provided by the number and the diversity of the stakeholders and, for this reason, defining the main "extremal complexity indicators" means defining the main areas of interest of the involved stakeholders.

The stakeholders can be divided into two groups, considering if they are internal and external to process. Applying (Kian Manaesh Rad, 2014) taxonomy on a space exploration case study, internal stakeholders can have different needs:

1. *Final mission needs* (i.e. related to the project delivery);
2. *Technological needs* (i.e. related to the project characteristics);
3. *Scientific needs* (i.e. related what the project has to provide);

On the contrary, external stakeholders are mainly interested in:

4. *Political needs* (i.e. related to legal issues, regulations and politics);
5. *General public needs* (i.e. related to social issues);
6. *Economic needs* (i.e. related to the economy and financial issues).

Every stakeholder can be related to one of these six categories, proposing requirements and priorities according to it. This is true also in the example of HERACLES MC, where the six categories can be defined as follows:

- *The final mission area*, considering Space Agencies or organization;
- *The political area*, considering all the stakeholders coming from governments and political organizations;

- *The general public area*, considering all the stakeholders related to news distribution and social media;
- *The economic area*, considering all stakeholders related to resources distribution (e.g. inside space agencies or governments);
- *The scientific area*, considering in this group all the stakeholders related to the scientific payload operations and results (e.g. mission users);
- *The technological area*, considering in this category engineers and operators related to technological enhancement.

Different areas can require different types of strategies that will have to be considered according to the relevance of the stakeholder category over the case study. Applying to an example of a space exploration case study such as HERACLES MC, the rational explained in (Graham, 2006), it is possible to order the six previous categories to stakeholders influence and interest into the roadmapping process under analysis (Figure 14). Table 7 shows examples of criteria that stakeholders interested in HERACLES MC enhancement can ask.

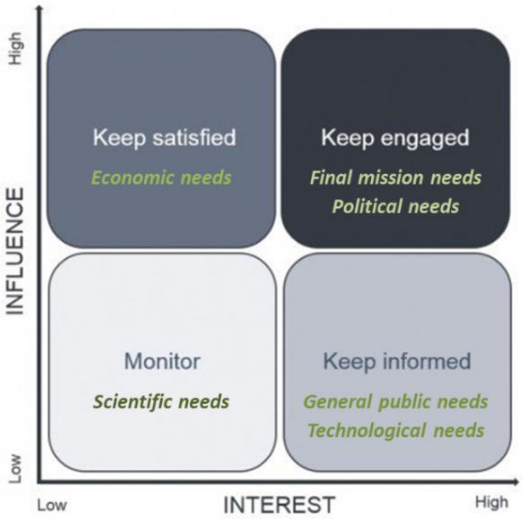


Figure 14: Stakeholders' Grid.

Strategies are important input for a roadmapping activity, but are not the only input that stakeholders have to provide. Indeed, with available resources and desired TRL, it is important to allow the user to define external constraints that will be helpful for obtaining a plausible result and this is true particularly in the update of an existing roadmap. Indeed, it is possible that only one or more element have to be update or that, thanks to a change of strategy, one or more elements will obtain more resources and for this reason an higher final maturity.

Table 7: Criteria examples.

Stakeholder area	Criteria description	Example of parameter
Final mission area	Higher integration capability	IRL
	Higher range of performances for the technologies considered	Normalized value comparing the required performance with the expected one
	Most required/applicable between the MCs	Link between technologies and MCs
	Technology is critical for enabling envisaged roles in identified missions	Technology is critical for enabling envisaged roles in identified missions)
	Programmatic aspects situation for the specified technology	Planned TRL progression vs. missions development and launch date
Political area	Technologies not developed by other agencies/nations	Ratio between a binary index on if a tech is found or not on other roadmaps and the difference of the TRL (ESA and not)
	Uniqueness of the technological solution defined	Number of technologies with similar performances (or) technologies in the same subject (or) programmes
	Application potential to assure a sustained role to European industries	MCs/BBs/OCs where technologies are applicable
	Technology fills identified gap at international level	TRL (ESA and not), the budget available, the number of initiatives
General public area	Human missions applicability	Man-tended technologies
	Technologies applicable also on Earth	Number (or potential) of initiatives or application on ground
	Most required/applicable between the OCs	Link between technologies and OCs
Economic area	Higher reusability	Link between technologies and BBs
	Lower technology costs	Technology Costs at Completion (CaC) from actual to required TRL
	Affordability of the specified technology	CaC vs. available Budget
	Presence/Lack of initiatives to enhance the defined technology	Available Budget
Scientific area	Human missions applicability	Man-tended technologies
	Technologies applicable on different planet surfaces	Surface/atmospheric technologies
	Innovative technologies	TRL (and/or) the link with OCs
Technological area	Develop not studied technologies	TRL
	End the development of advanced techs	TRL
	Lower difficulty	AD2 (or) risk
	Develop techs for new application	SRL
	End the development of techs for under study application	SRL

Moreover, constraints may be applied to each roadmap element category. These constraints refer to stakeholders' needs and have to be derived in preliminary activities.

A user can be interested in focusing only on some design features (e.g. a certain number of stages) and for this reason in reducing the BBs, OCs, MCs and technologies lists to the elements that verify this constraint.

2.3. Roadmap Development

Thanks to the preliminary activities, all the mission and programmatic requirements have been defined and the roadmapping process can start. This section has to be intended as an initial familiarization with the proposed methodology for roadmap definition and update (i.e. TRIS) through some examples, supposing already performed all the required preliminary activities. The final proposed method will be explained later.

2.3.1. Roadmap Elements Definition and Characterization Process

The very first step of a common roadmapping process has to involve the study of the elements involved in the process. Two particular cases can be considered. Indeed, it is different when the roadmap elements have to be defined for a new roadmapping process and when the update of an existing roadmap has to be started. In both cases, it remains true that, for how the four roadmap elements groups are defined, they are strictly related applying Systems Engineering theories.

2.3.1.1. TAs Features

Starting from TAs, it is possible to analyse literature to define common features (ESA, 2015b; Viscio, 2013a, 2014a). In space exploration case studies, roadmaps encompass roughly the same major TAs, even though they are organised in different groups. This becomes apparent considering that ESA's TAs derive from the agency's departments where R&D is carried out (ESA, 2015b). At Politecnico di Torino instead, TAs were identified in a context where the aim was to build an incremental scenario towards a Mars mission (namely NASA DRA 5.0 (NASA JSC, 2009)), trying to define a list of sub-systems that might be involved in the final mission. Table 8 compares these two references taking into account all technological sub-areas making up the broader TAs identified by both institutions. The TAs listed have to be intended not only like significant sub-systems, but also like research areas delivering tangible improvements, which can be quantified by means of their TRL.

Usually TAs are not directly divided into technologies, but further categorizations are required. This is inline also with a System Design Process based on a Systems Engineering approach: every product is divided into sub-products defining the Products Tree levels in such a way to be related to a specific Functional Tree level. According to (ESA, 2015b) and (NASA, 2017), TAs are divided into Technology Subjects, that are general entities that may include several technologies combined together in different ways and that are possible components categories. It is important to note, that, being them defined as component categories, they have to be further divided to specify the component features or properties. Technology Subjects possess different types of properties: these properties may be assigned qualitative and/or quantitative values, in terms of sets (of qualitative values, e.g. property "energy source" might be equal to {solar; fuel cells; batteries}) and/or numerical ranges (e.g. "leakage" = [0.1, 1] kg/day).

Table 8: (ESA, 2015a) and (Viscio, 2014a, 2013a) example of TAs**.**

ESA	Politecnico di Torino
1. Life Support & Asset Protection	8. Life Support 10. Environment, Humans and Safety
2. Novel Energy Production & Storage	2. Power
3. Advanced Propulsion	9. Propulsion
4. Automation & Robotics	4. Robotics & Automation 5. Avionics & Harnesses 6. Communications
5. Thermal, Thermal Protection System (TPS) & Aerothermodynamics Aspects	3. Thermal 11. Atmospheric Descent & Landing
6. Adv. Structures & Mechanisms Applications	1. Structures & Mechanisms
7. GNC & related Sensors	7. Attitude, Guidance & Navigation 4. Robotics & Automation
8. Communication, Remote Sensing & Imaging	6. Communications
9. Systems & Processes	

These properties not only are related to requirements that describe a specific Technology Subject behaviour, but usually are better expressed in the technologies. Note that the values that these properties assume are dependent on the technology level of the related element, and so they need to be updated as missions and technologies progress. Looking at different space exploration systems, different sub-systems (i.e. Technology Subjects) can be supposed: atmosphere containment system, environmental control system, environmental protection, structure & mechanisms, electrical power generation & management system, thermal control system, data handling system, communication system, crew support system, attitude determination and control system, guidance and navigation system, propulsion system, entry and landing system, observation system, mobility system, digging & grabbing system and resources extraction system. Each Technology Subject can be studied, specifying the most important properties. For example, focusing on the atmosphere containment system, the following properties can be defined: *pressure containment* (maximum value of differential pressure expressed in Pa), *leakage* (maximum leakage in kg/day), *overpressure control* (maximum over-pressurization of containment), *number of Extra Vehicular Activity (EVA) accesses* to the structure and *number of on ground accesses* to the structure.

2.3.1.2. OCs Features

It is possible to analyse literature (ESA, 2015b; Viscio, 2014a, 2013a) to define common features also in analysing OCs. OCs derivation is highly related to the aims driving the roadmapping processes. Indeed, while ESA's OCs derive from the agency's internal needs and projects, in the work carried out at Politecnico di Torino OCs were identified in a context where the aim was to build an incremental scenario towards a specific Mars mission. In both cases, OCs represent areas of high importance that have to influence development of TAs and they are derived combining a functional basis (e.g. "transfer") with one or more features (e.g. "cargo") or performance types (e.g. "high capacity"). This particular feature gives to a generic OCs the potentiality to be transformed in a performance requirement once the performance type is specified. For example, ESA identified 13 OCs such as "*Rendez-Vous (RdV) and Docking with (non) collaborative target*" and "*High Capacity Cargo Transfer*" (ESA, 2015a).

As discussed above, starting from OCs and with the aim to improve them might seem necessary to define a quantitative parameter to express the current state of each OC. First, being a generic OC defined as a high-level performance requirement is possible to define a list of technologies able to guarantee this requirement. This means that, when these technologies' TRLs increase, also the OCs is enhanced. The latter are already quantified by means of TRL, which might be exploited for computing a weight able to size the level of OCs maturity (i.e. a sort of pseudo-TRL for OCs). Just suppose generic OC A linked to two generic technologies i and j, required and applicable respectively. Then, the pseudo-TRL can be evaluated as (Cresto Aleina, 2016c):

$$\text{pseudo} - \text{TRL}_A = \frac{\text{TRL}_i + \text{TRL}_j}{r_i + a_j}\text{, where } r_i \geq a_j \tag{2.1}$$

The values of r_i, a_j may be defined by the user but they need to remain the same throughout the different OCs and can be considered as weights related to the impact over the design of specific links that exist between different roadmaps elements (e.g. between technologies and OCs in this particular case). For this reason, required links will weigh more, having a higher impact on the design. This means also that the smaller is the pseudo-TRL, the bigger is the priority with which that OC will be addressed. For instance one could set a_j=1.00 and r_i=2.00. Finally, this parameter, even if is related to an ordinal parameter such as the TRL, is there intended to be a weight and, for this reason is not related to defined levels. It has to be noticed that, for how this parameter is defined, it is dependent from Technologies TRL, their number and the impact over the design of the different applied technologies (Figure 15 and Figure 16).

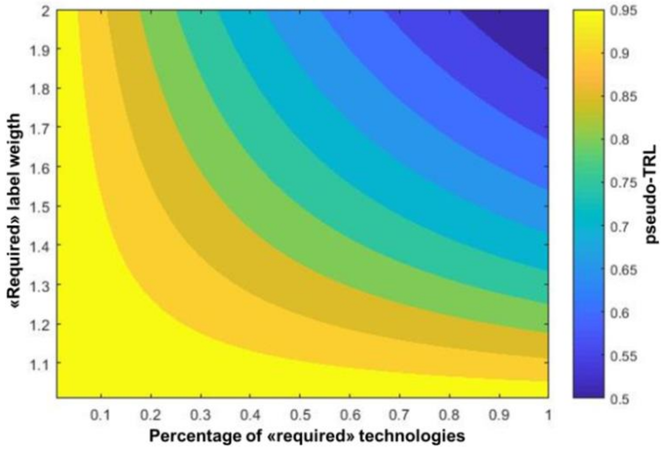


Figure 15: Diagram relating Pseudo-TRL, number of technologies required and "required" weight.
"Applicable" weight has been supposed at 1 and technologies at TRL 9 for simplicity.

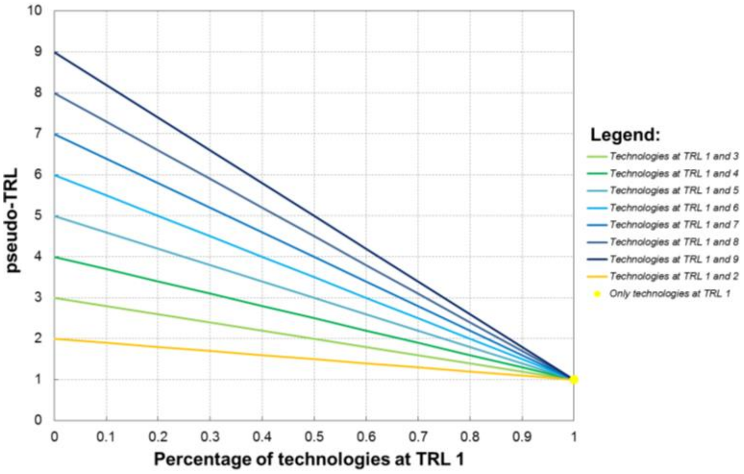


Figure 16: Diagram relating Pseudo-TRL, percent of technologies at different TRL.
"Applicable" weight has been supposed at 1 and combinations of only two TRL (one of which at 1) are proposed for simplicity.

2.3.1.3. BBs Features

BBs are a quite recent element in space exploration roadmaps. Indeed, they were not present in the first version of ESA's Roadmaps. Unfortunately, their late introduction may lead to misunderstandings in their application, thus running the risk of not exploiting them.

A BB is a physical element that exploits the concept of "modularity" in order to be related to one or more specific MCs, OCs or TAs. In addition, it needs not to be described with a top-down approach as done with the TAs (e.g. TA *Novel Energy Production & Storage* contains photovoltaic, nuclear, electrochemical, etc. power). A significant categorization of the BBs currently found in literature (ESA, 2015b) could be between *sub-systems* (defined as a collection of different products that together produce an effect not obtainable by the single elements) and *systems* (defined as a particular kind of product that can represent an individual system inside a SoS).

These two categories are different levels of detail might be useful to represent different applications and developments: indeed, it is possible to be interested in developing a specific and simple BB (i.e. a sub-system) or a more complex one (i.e. a system) also considering systems' interactions and mission target needs. It has to be said that in applying a System Design Process approach, BBs, TAs, Technology Subjects and technologies belong to specific Products Tree levels and the previous categorization inside BBs list will not be significant anymore. It remains true that the level of the BBs considered is strictly related to the scenario and the stakeholders' needs defined in the preliminary activities. In addition, notice that since missions are made up of BBs, BBs should be as detailed as necessary to identify "every possible mission". Besides, it is important to limit BBs to a reasonable number as done with TAs, in order to be able to handle them. For example, ESA identified 22 BBs such as "*visual navigation, hazard detection and avoidance system*" (sub-system) and "*sample return Earth re-entry capsule*" (system) (ESA, 2015a).

Common BBs categories based on the current space exploration strategies (ISECG, 2018) are the following: Habitable Module, Transportation Module, Robotic Infrastructure, In-Situ Resources Utilization (ISRU) Infrastructure and Satellite. An example could be the BB *Habitable Module* that is divided into smaller products depending on it (i.e. sub-systems) (Table 9).

Table 9: Sub-systems and BBs map.

	Habitable module	**Transportation module**	**Robotic infrastructure**	**ISRU infrastructure**	**Satellite**
Atmosphere containment	X	X			
Environmental control	X	X			
Environmental protection	X	X	X	X	X
Structure & mechanisms	X	X	X	X	X
Electrical power gen. & man.	X	X	X	X	X
Thermal control	X	X	X	X	X
Data handling	X	X	X	X	X
Communication	X	X	X	X	X
Crew support	X	X			
Attitude determination & ctrl		X			X
Guidance and navigation		X			X
Propulsion		X			
Entry and landing		X			
Observation			X		X
Mobility			X		
Digging & Grabbing			X		
Resources extraction				X	

2.3.1.4. MCs Features

MCs roadmap element group usually contains all the events that might happen and that can enhance the current technological expertise. Examples of MCs can be found in ESA Space Exploration Technology Roadmaps (ESA, 2015b). As already explained, already planned missions are significant only for the current situation analysis and not in a new planning proposal. On the contrary, examples of under approval MCs can be directly found looking at the 10 programmes proposed in (ESA, 2015b) to be related to the technologies analysed.

Considering potential missions, some missions have been identified not only considering potential future missions, but also considering the possibility to suggest some demo mission in order to increase the TRL where a fully operational mission cannot be carried out. The following MCs have been identified:

1. *6 Technology Maturation Activities in ground facilities:* theoretical principles formulation (TRL 1-2), analytical proof (TRL 3), experimental proof (TRL 3), lab. components/ breadboard validation (TRL 4), components/ breadboard validation in not controlled environment (TRL 5), system/ sub-system prototype demonstration in not controlled environment (TRL 6);
2. *3 Technology Maturation Activities in LEO:* components/breadboard validation (TRL 5), system/ sub-system prototype demo. (TRL 6),

complete system flight qualification (TRL 7);

3. *2 potential missions targeting the Moon:* lunar human assisted Sample return, human lunar surface;
4. *1 potential mission targeting Mars:* human Mars.

The previous list depicts all the possible future MCs and the demo mission that can be actually performed according to the international roadmapping efforts (ISECG, 2018) performed at the time of ESA second roadmapping activity (ESA, 2015b). Finally, every MC considered has to be attached to some properties in order to describe its features in order to apply them in the final planning. Examples of MC properties that can be found in (ESA, 2015b) are the following ones: *MC timing* (such as starting time, launch date and ending time) and *financial resources* such as resources amount or kind of fund used.

2.3.1.5. Roadmap Elements Update Process

The evolutionary character of the roadmaps requires them to be updated at least periodically: updates are the results of specific plans to increase technological maturity in a specific scenario, once these plans are accomplished and new one have to be defined. This implies that pseudo-TRLs advance, mission scenarios progress and technologies TRL increase. Also the properties in Technology Subjects have to be updated if the respective technology has undergone an improvement. An example of update of an existing roadmap has been provided in (Saccoccia, 2017) in analysing the update of ESA Space Exploration Technology Roadmaps. In this process, a method able to generate roadmap elements according to Systems Engineering theories and a current situation analysis has been proposed in order to check for new BBs, OCs and MCs (Figure 17). In particular, the list of OCs has been derived looking for every activity related to transportation, operations, in-space servicing and surface support (Figure 18), thanks to a functional tree.

In addition, it has to be remembered that MCs are the “action items” with which the TRL increase path is proposed and analysed. In this context, the hypothetical missions are potential MCs derived to cover all the current and future possible MCs or at least, if grouped, every part of them. Hypothetical missions are there proposed starting from the definition of all possible mission phase segment that can be performed between two different strategic targets. These mission phase segments can be then grouped according to the type of starting and ending point (e.g. strategic targets, Figure 19). Additional data that might be considered in proposing new missions are the mission approach (i.e. permanently inhabited, man-tended or robotic) and the mission duration (i.e. short, long or sortie). It has to be underlined that the targets defined in this case are in line with previous ESA Space Exploration Technology Roadmaps (ESA, 2015b) and other international space exploration roadmapping efforts (ISECG, 2018).

Finally, connecting hypothetical missions categories and the list of OCs defined, it is possible a certain number of required BBs (Figure 20) mapping them on the previous two roadmap elements. This map can be also useful to propose new roadmap paths.

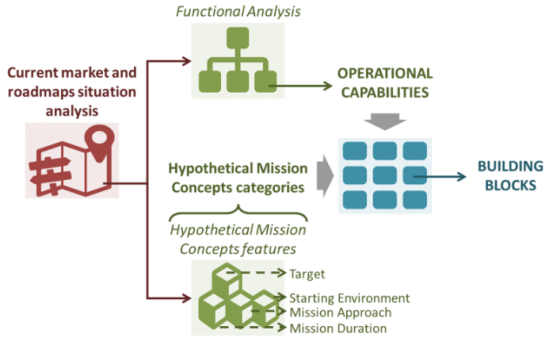


Figure 17: Generic scheme of the process followed for BBs definition.

Figure 18: OCs' categories.

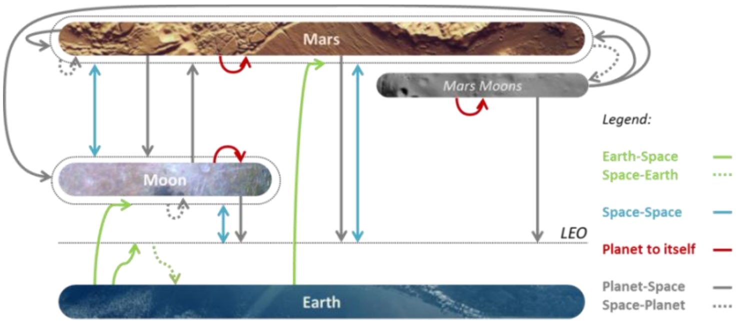


Figure 19: Hypothetical MCs' categories.

			List of Hypothetical Mission Concepts Categories					
			Space-Earth	*Earth-Space*	*Space-Space*	*Planet-Space*	*Space-Planet*	*Planet to itself*
Operational Capabilities	*Transportation Operational Capabilities*	1. High performance human transfer	**Entry Module**		**Transfer Module**		**Entry Module**	**Spaceplane**
		2. High capacity cargo transfer	**Entry Module**		**Space Tug**		**Entry Module**	**Spaceplane**
		3. Orbit maintenance (Cargo)		**Service Module**	**Service Module**	**Service Module**		
		4. Orbit maintenance (Human)		**Service Module**	**Service Module**	**Service Module**		
		5. Cargo entry	**Entry Module**				**Entry Module**	**Entry Module**
		6. Manned entry	**Entry Module**				**Entry Module**	**Entry Module**
		7. Surface high precision cargo D&L	**Lander**				**Lander**	**Lander**
		8. Surface high precision cargo Descent & Impact	**Penetrator**				**Penetrator**	
		9. Surface high precision manned D&L	**Lander**				**Lander**	**Lander**
		10. Manned take-off/lift-off and ascent		**Launcher**		**Ascent Module**		**Spaceplane**
		11. Cargo take-off/lift-off and ascent		**Launcher**		**Ascent Module**		**Spaceplane**
	Operations Capabilities	12. In space multiple element assembly		**In-space Node**	**In-space Node**	**In-space Node**		
		13. Communications (high DR)	**Communication Network**	**Communication Network**	**Communication Network**	**Communication Network**	**Communication Network**	**Communication Network**
		14. Low-g bodies anchoring					**Anchoring Module**	**Anchoring Module**
		15. Sample analysis and containment				**Sampling Lab**	**Sampling Lab**	**Sampling Lab**
		16. Robotic tele-operations		**Tele-operated Manipulator**	**Tele-operated Manipulator**	**Tele-operated Manipulator**	**Tele-operated Manipulator**	**Tele-operated Manipulator**
	In-Space Servicing Operational Capabilities	17. In-Space propellant management	**Refuelling Module**	**Refuelling Module**	**Refuelling Module**	**Refuelling Module**	**Refuelling Module**	
		18. In-Space long term propellant storage	**In-space Depot**	**In-space Depot**	**In-space Depot**	**In-space Depot**	**In-space Depot**	
		19. In-Space high capacity power generation and management	**In-space Power Module**	**In-space Power Module**	**In-space Power Module**	**In-space Power Module**	**In-space Power Module**	
		20. In-Space life support		**Greenhouse**	**Greenhouse**	**Greenhouse**		
		21. In-Space short-term human habitability	**Entry Module**	**Launcher**	**Transfer Module**	**Ascent Module**	**Entry Module**	
		22. In-Space long-term human habitability		**In-space Habitable Module**	**In-space Habitable Module**	**In-space Habitable Module**		
		23. In-Space radiation protection		**Radiation Shield**	**Radiation Shield**	**Radiation Shield**		
		24. In-Space autonomous supporting robotics		**In-space Servicing Aids**	**In-space Servicing Aids**	**In-space Servicing Aids**		
		25. In-Space IVA, EVA, IEVA	**Space Suit**	**Space Suit**	**Space Suit**	**Space Suit**	**Space Suit**	
		26. In-space interface EVA		**Airlock**	**Airlock**	**Airlock**		
	Surface Support Operational Capabilities	27. Surface multiple element assembly					**Surface Node**	**Surface Node**
		28. Surface high capacity power generation and management				**Surface Power Station**	**Surface Power Station**	**Surface Power Station**
		29. Surface life support					**Greenhouse**	**Greenhouse**
		30. Surface short-term human habitability					**Lander**	**Lander**
		31. Surface long-term human habitability					**Surface Habitable Module**	**Surface Habitable Module**
		32. Surface radiation protection					**Radiation Shield**	**Radiation Shield**
		33. Surface robotics					**Surface Servicing Aids**	**Surface Servicing Aids**
		34. ISRU				**ISRU Plant**	**ISRU Plant**	**ISRU Plant**
		35. Surface long term propellant storage				**Surface Depot**	**Surface Depot**	**Surface Depot**
		36. Surface high capacity propellant management				**Refuelling Station**	**Refuelling Station**	**Refuelling Station**
		37. Surface IVA, EVA, IEVA					**Space Suit**	**Space Suit**
		38. Surface interface EVA					**Airlock**	**Airlock**
		39. Low-g bodies human surface mobility					**Rover**	**Rover**
		40. Low-g bodies cargo surface mobility					**Rover**	**Rover**

Figure 20: BBs map.

2.3.2. Applicability Analysis

Having defined the elements involved in the roadmapping process, in order to propose a rational methodology able to propose a roadmap in a semi-automatic process, the links between the different elements have to be analysed and sized. In particular, Applicability Analysis is intended as the analysis performed to map one element of the methodology onto the others. For example, if a generic stakeholder wants to enhance an OC (or a group of them), the tool has to derive the most suitable technologies to do so and the key BBs that combined in MCs will succeed in achieving the established goal. As Figure 21 shows, depending on the stakeholder needs, he/she can start the analysis from any element and then proceed along a predetermined path.

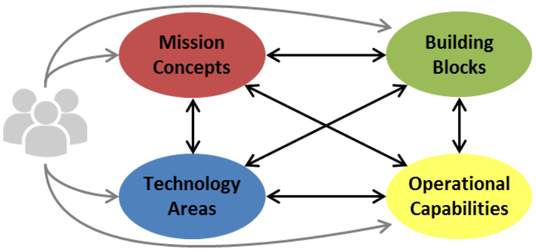


Figure 21: MC, BB, TA and OC are all linked between them and different path are possible according to stakeholders' needs.

Part of this analysis is already defined if a System Design Process approach is proposed for the previous phase: indeed, it is easy to understand that the four elements are strictly related one to the other by definition and that the application of Systems Engineering tools can drive the identification of these relationships. In particular, thanks to Systems Engineering tools and theories is possible to define possible links between elements, but these links have to be sized in order to support the roadmap definition. It has to be said, that Applicability Analysis has been already used in (Viscio, 2014) to achieve weighted maps between roadmaps elements. Introducing the proposal of demo mission in already planned operational missions to (Viscio, 2014), each single element is related to the others through the following labels:

- *Applicable* (i.e. relationship between two elements relevant but not strictly needed by the overall mission/architecture);
- *Test* (i.e. combination never applied before and considered in a mission planned not specifically for validation purposes);
- *Demo* (i.e. combination never applied before and considered in a

mission planned specifically for validation purposes);

- *Required* (i.e. relationship between two elements highly impacting on);
- *Not applicable* (i.e. no combination is possible).

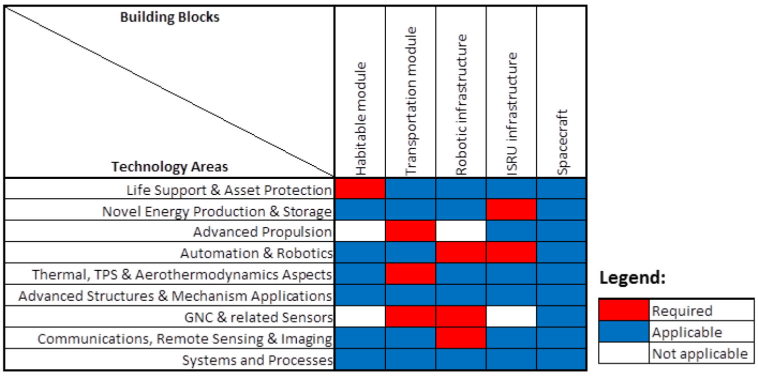
Thanks to these labels, it is possible to define different types of applicability maps. Based on the Functional Analysis the different labels can be defined simply knowing the combinations actually required from the current roadmap. Methodologies to relate the different labels with stakeholders' needs have to be proposed in order to foreseen these labels according to current strategies.

If the purpose is to relate different elements types, not considering a time reference, two types of applicability analyses are of interest in our case:

- *Applicability of TAs/technologies onto OCs* where the labels demo and test are not applied;
- *Applicability of TAs/technologies onto BBs*, where, again, the labels demo and test cannot be applied.

It has to be underlined that having all the applicability maps related to a common element (such as technologies) can lead to a simplification of the process, for example in the prioritization process. Applying these definitions to (ESA, 2015b) remembering the elements proposed in the previous sections, it is possible show an example of applicability analyses at a first level of OCs, TAs and BBs (Figure 22 and Figure 23).

Going further into details, the same applicability analyses can be re-applied at second and third level to each subclass of technologies. However, getting to a lower level requires specific and detailed information about each technology: inputs from experts become surely important. As far as the inputs from experts are concerned, in order to perform an Applicability Analysis between technologies, it could be important to understand which technologies can be tested together. An alternative could be to have an indication of the different tests and/or environments as expressed in the TRL definition (e.g. laboratory environment, relevant environment, operational environment or mission environment) per each technology. With this information, an estimation of the TRL increase could be performed and suggested automatically by TRIS. For simplicity, the third level maps will not be reported, but an example can be provided at Technology Subject level (Figure 24 and Figure 25).

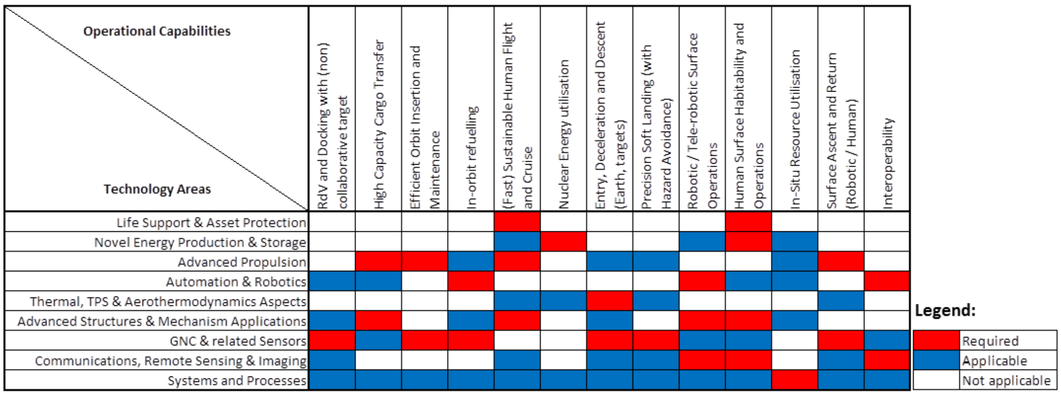


Building Blocks Technology Areas	Habitable module	Transportation module	Robotic infrastructure	ISRU infrastructure	Spacecraft
Life Support & Asset Protection	🟥	🟦	🟦	🟦	🟦
Novel Energy Production & Storage	🟦	🟦	🟦	🟥	🟦
Advanced Propulsion	⬜	🟥	⬜	🟦	🟦
Automation & Robotics	🟦	🟦	🟥	🟥	🟦
Thermal, TPS & Aerothermodynamics Aspects	🟦	🟥	🟦	🟦	🟦
Advanced Structures & Mechanism Applications	🟦	🟦	🟦	🟦	🟦
GNC & related Sensors	⬜	🟥	🟥	⬜	🟦
Communications, Remote Sensing & Imaging	🟦	🟦	🟥	🟦	🟦
Systems and Processes	🟦	🟦	🟦	🟦	🟦

Legend:

🟥	Required
🟦	Applicable
⬜	Not applicable

Figure 22: Applicability Analysis between the first level of BBs and TAs.
"Required" combinations are in red, "applicable" in blue and "not applicable" in white.



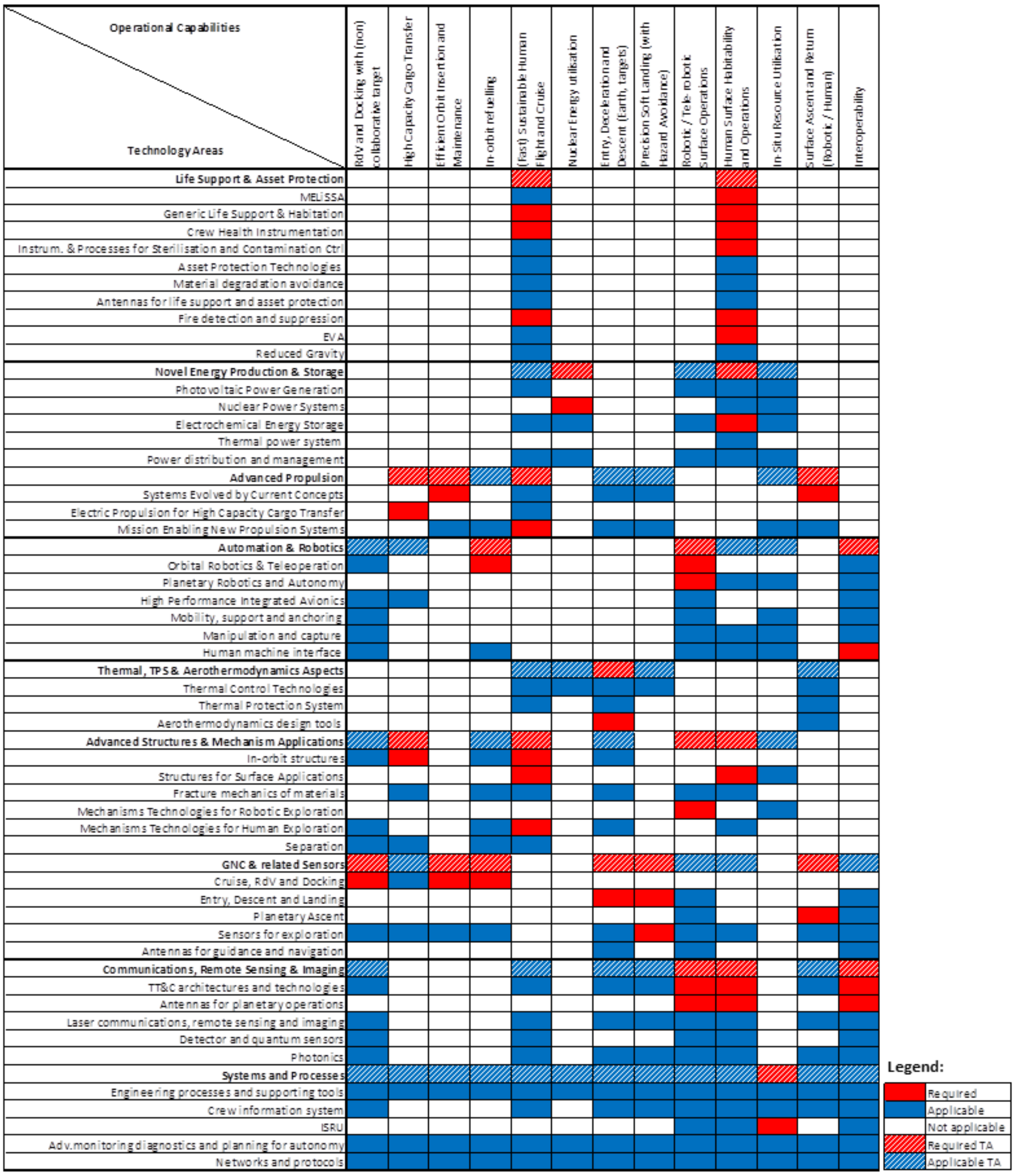
Operational Capabilities Technology Areas	RdV and Docking with (non) collaborative target	High Capacity Cargo Transfer	Efficient Orbit Insertion and Maintenance	In-orbit refuelling	(Fast) Sustainable Human Flight and Cruise	Nuclear Energy utilisation	Entry, Deceleration and Descent (Earth, targets)	Precision Soft Landing (with Hazard Avoidance)	Robotic / Tele-robotic Surface Operations	Human Surface Habitability and Operations	In-Situ Resource Utilisation	Surface Ascent and Return (Robotic / Human)	Interoperability
Life Support & Asset Protection	⬜	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜	🟥	⬜	⬜	⬜
Novel Energy Production & Storage	⬜	⬜	⬜	⬜	🟦	🟥	⬜	⬜	🟦	🟥	🟦	⬜	⬜
Advanced Propulsion	⬜	🟥	🟥	🟦	🟥	⬜	🟦	🟦	⬜	⬜	🟦	🟥	⬜
Automation & Robotics	🟦	🟦	⬜	🟥	⬜	⬜	⬜	⬜	🟥	🟦	🟦	⬜	🟥
Thermal, TPS & Aerothermodynamics Aspects	⬜	⬜	⬜	⬜	🟦	🟦	🟥	🟦	⬜	⬜	⬜	🟦	⬜
Advanced Structures & Mechanism Applications	🟦	🟥	⬜	🟦	🟥	⬜	🟦	⬜	🟥	🟥	🟦	⬜	⬜
GNC & related Sensors	🟥	🟦	🟥	🟥	⬜	⬜	🟥	🟥	🟦	🟦	⬜	🟥	🟦
Communications, Remote Sensing & Imaging	🟦	⬜	⬜	⬜	🟦	⬜	🟦	🟦	🟥	🟥	⬜	🟦	🟥
Systems and Processes	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟥	🟦	🟦

Legend:

🟥	Required
🟦	Applicable
⬜	Not applicable

Figure 23: Applicability Analysis between OCs and TAs.

Another type of Applicability Analysis between different types of elements is required to complete the cycle: *applicability of MCs onto BBs or TAs/technologies*. An example is provided in Figure 26. A peculiarity of this map is that, being related to MCs, this is the only map with a sort of time reference and for this reason it will be possible to introduce the "demo" and "test" labels. In particular, this is possible after an application of the proposed methodology after having defined which MCs can be used for test or demo purposes. The definition of "demo" and "test" combination is surely related to the presence of demo missions. It has to be said that, these labels have to be considered sub-categories of "required" combinations, present when low TRLs are involved. It is possible to define a parameter able to rank these labels information. A parameter can be the percent of technologies under a certain TRL (e.g. 7 (Cresto Aleina, 2016c)) in every MCs, defining it at roadmap proposed and verified. For simplicity, this parameter can be called "demo%": if "demo%" is 100% the missions is a demonstrative, whereas if the "demo%" is 0% the missions is fully operational.

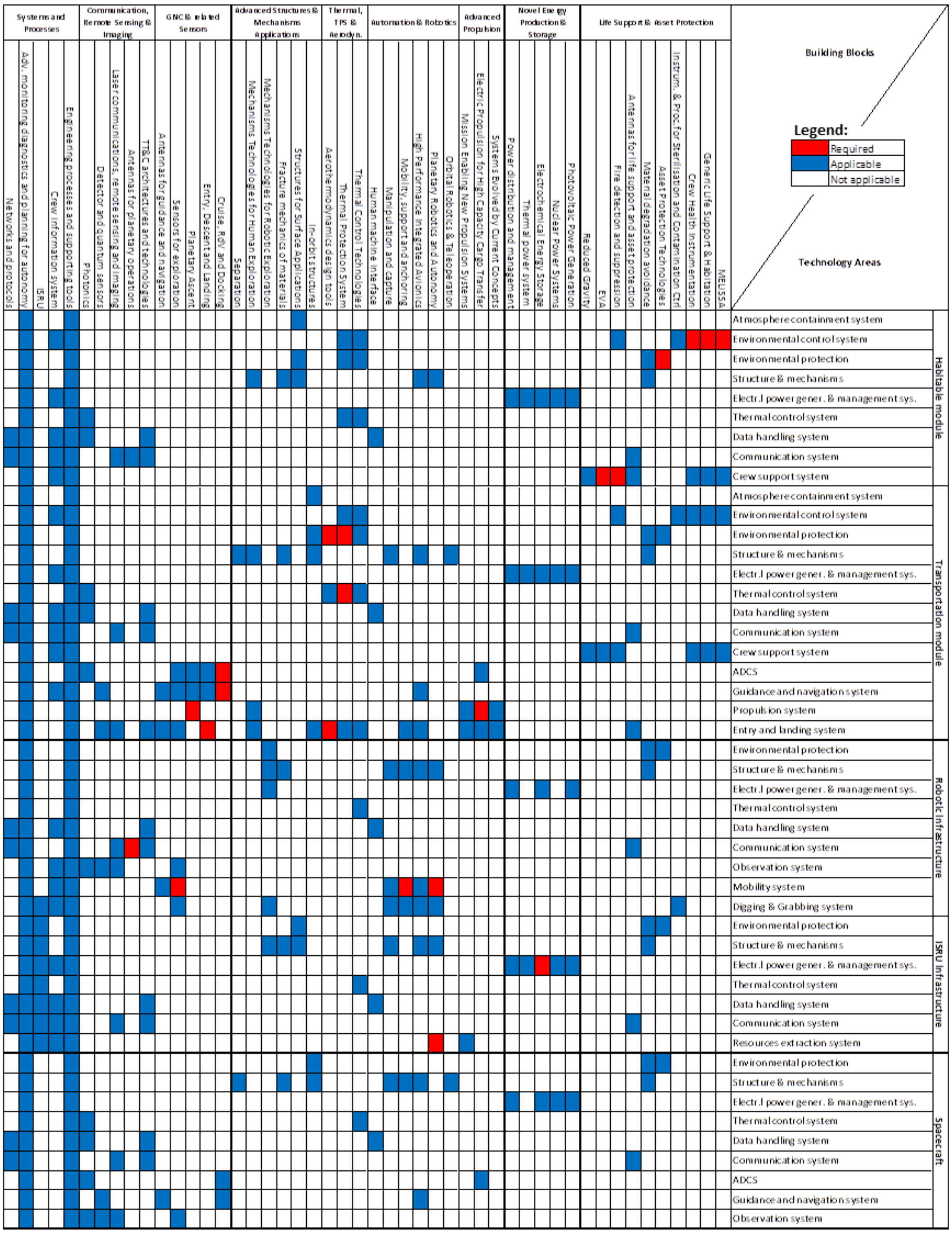


Operational Capabilities / Technology Areas	Rdv and Docking with (non) collaborative target	High Capacity Cargo Transfer	Efficient Orbit Insertion and Maintenance	In-orbit refuelling	(Fast) Sustainable Human Flight and Cruise	Nuclear Energy utilisation	Entry, Deceleration and Descent (Earth, targets)	Precision Soft Landing (with Hazard Avoidance)	Robotic / Tele-robotic Surface Operations	Human Surface Habitability and Operations	In-Situ Resource Utilisation	Surface Ascent and Return (Robotic / Human)	Interoperability
Life Support & Asset Protection					▨					▨			
MELiSSA					🟦					🟥			
Generic Life Support & Habitation					🟥					🟥			
Crew Health Instrumentation					🟥					🟥			
Instrum. & Processes for Sterilisation and Contamination Ctrl					🟦					🟥			
Asset Protection Technologies					🟦					🟦			
Material degradation avoidance					🟦					🟦			
Antennas for life support and asset protection					🟦					🟦			
Fire detection and suppression					🟥					🟥			
EVA					🟦					🟥			
Reduced Gravity					🟦					🟦			
Novel Energy Production & Storage					▧	▨			▧	▨	▧		
Photovoltaic Power Generation					🟦				🟦	🟦	🟦		
Nuclear Power Systems						🟥				🟦	🟦		
Electrochemical Energy Storage					🟦	🟦			🟦	🟥	🟦		
Thermal power system										🟦			
Power distribution and management					🟦	🟦			🟦	🟦	🟦		
Advanced Propulsion		▨	▨	▧	▨		▧	▧			▧	▨	
Systems Evolved by Current Concepts			🟥		🟦		🟦	🟦				🟥	
Electric Propulsion for High Capacity Cargo Transfer		🟥			🟦								
Mission Enabling New Propulsion Systems			🟦	🟦	🟥		🟦	🟦			🟦	🟦	
Automation & Robotics	▧	▧		▨					▨	▧	▧		▨
Orbital Robotics & Teleoperation	🟦			🟥					🟥				🟦
Planetary Robotics and Autonomy									🟥	🟦	🟦		🟦
High Performance Integrated Avionics	🟦	🟦							🟦				🟦
Mobility, support and anchoring	🟦								🟦		🟦		🟦
Manipulation and capture	🟦								🟦	🟦	🟦		🟦
Human machine interface	🟦			🟦					🟦	🟦	🟦		🟥
Thermal, TPS & Aerothermodynamics Aspects					▧	▧	▨	▧				▧	
Thermal Control Technologies					🟦	🟦	🟦	🟦				🟦	
Thermal Protection System					🟦		🟦					🟦	
Aerothermodynamics design tools							🟥					🟦	
Advanced Structures & Mechanism Applications	▧	▨		▧	▨		▧		▨	▨	▧		
In-orbit structures	🟦	🟥		🟦	🟥		🟦						
Structures for Surface Applications					🟥					🟥	🟦		
Fracture mechanics of materials		🟦		🟦	🟦		🟦		🟦	🟦			
Mechanisms Technologies for Robotic Exploration									🟥		🟦		
Mechanisms Technologies for Human Exploration	🟦			🟦	🟥		🟦			🟦			
Separation	🟦	🟦		🟦	🟦								
GNC & related Sensors	▨	▧	▨	▨			▨	▨	▧	▧		▨	▧
Cruise, RdV and Docking	🟥	🟦	🟥	🟥									
Entry, Descent and Landing							🟥	🟥	🟦				🟦
Planetary Ascent									🟦			🟥	🟦
Sensors for exploration	🟦	🟦	🟦	🟦			🟦	🟥	🟦	🟦		🟦	🟦
Antennas for guidance and navigation							🟦		🟦				🟦
Communications, Remote Sensing & Imaging	▧				▧		▧	▧	▨	▨		▧	▨
TT&C architectures and technologies	🟦				🟦		🟦	🟦	🟥	🟥		🟦	🟥
Antennas for planetary operations									🟥	🟥			🟥
Laser communications, remote sensing and imaging	🟦				🟦		🟦	🟦	🟦	🟦		🟦	🟦
Detector and quantum sensors	🟦				🟦				🟦	🟦			🟦
Photonics	🟦				🟦		🟦	🟦	🟦	🟦		🟦	🟦
Systems and Processes	▧	▧	▧	▧	▧	▧	▧	▧	▧	▧	▨	▧	▧
Engineering processes and supporting tools	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Crew information system	🟦				🟦		🟦	🟦	🟦	🟦	🟦	🟦	🟦
ISRU									🟦	🟦	🟥		🟦
Adv.monitoring diagnostics and planning for autonomy	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Networks and protocols	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

Legend:

🟥	Required
🟦	Applicable
	Not applicable
▨	Required TA
▧	Applicable TA

Figure 24: Applicability Analysis between OCs and TAs (in bold type) or Technology Subject (i.e. the second level of TAs).

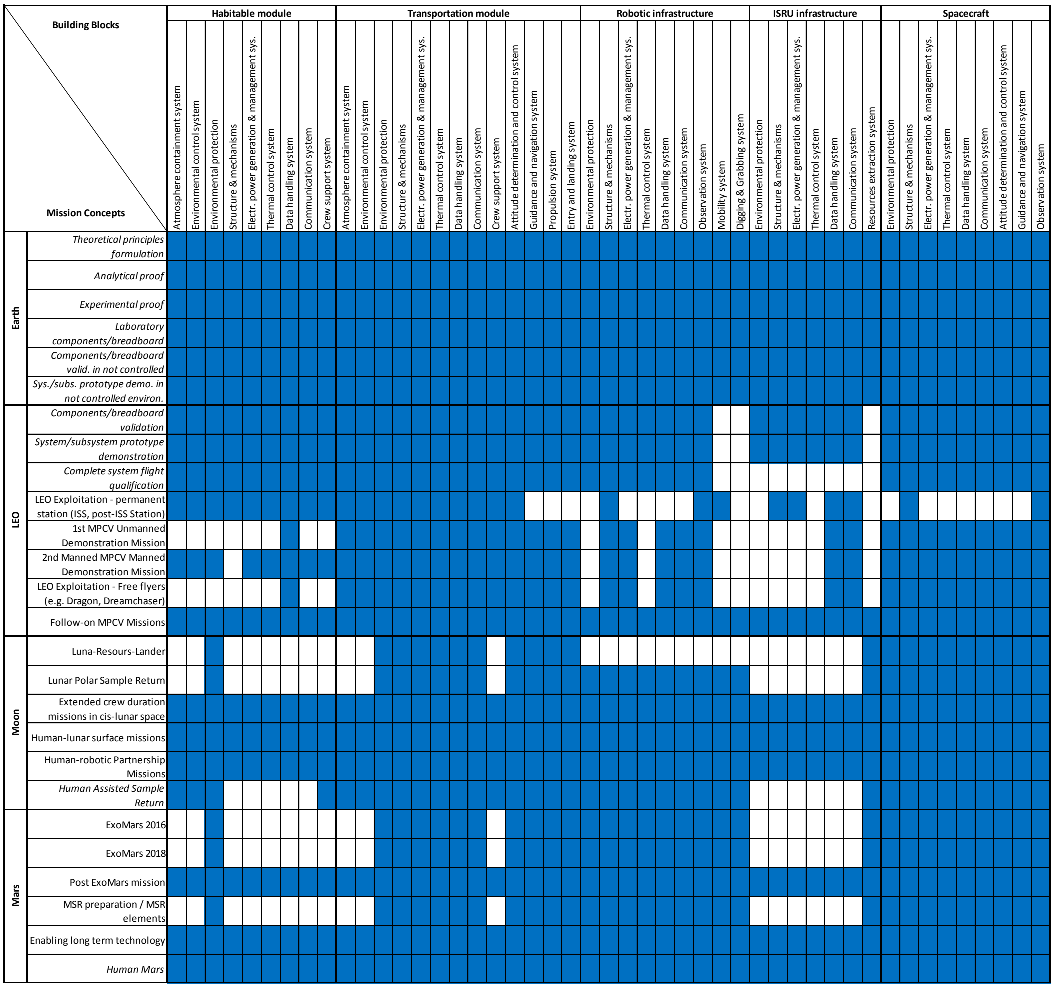


Legend:

🟥 Required
🟦 Applicable
⬜ Not applicable

	Building Blocks	Systems and Processes					Communication, Remote Sensing & Imaging					GNC & related Sensors					Advanced Structures & Mechanisms Applications						Thermal, TPS & Aerodyn.			Automation & Robotics						Advanced Propulsion			Novel Energy Production & Storage					Life Support & Asset Protection									
	Technology Areas	Networks and protocols	Adv. monitoring diagnostics and planning for autonomy	ISRU	Crew information system	Engineering processes and supporting tools	Photonics	Detector and quantum sensors	Laser communications, remote sensing and imaging	Antennas for planetary operations	TT&C architectures and technologies	Antennas for guidance and navigation	Sensors for exploration	Planetary Ascent	Entry, Descent and Landing	Cruise, RdV and Docking	Separation	Mechanisms Technologies for Human Exploration	Mechanisms Technologies for Robotic Exploration	Fracture mechanics of materials	Structures for Surface Applications	In-orbit structures	Aerothermodynamics design tools	Thermal Protection System	Thermal Control Technologies	Human machine interface	Manipulation and capture	Mobility, support and anchoring	High Performance Integrated Avionics	Planetary Robotics and Autonomy	Orbital Robotics & Teleoperation	Mission Enabling New Propulsion Systems	Electric Propulsion for High Capacity Cargo Transfer	Systems Evolved by Current Concepts	Power distribution and management	Thermal power system	Electrochemical Energy Storage	Nuclear Power Systems	Photovoltaic Power Generation	Reduced Gravity	EVA	Fire detection and suppression	Antennas for life support and asset protection	Material degradation avoidance	Asset Protection Technologies	Instrum. & Proc. for Sterilisation and Contamination Ctrl	Crew Health Instrumentation	Generic Life Support & Habitation	MELISSA
Habitable module	Atmosphere containment system		🟦			🟦															🟦																											
	Environmental control system		🟦		🟦	🟦																		🟦	🟦																	🟦				🟦	🟥	🟥	🟥
	Environmental protection		🟦			🟦															🟦			🟦	🟦																				🟦	🟥				
	Structure & mechanisms		🟦			🟦												🟦		🟦	🟦								🟦	🟦															🟦					
	Electr.l power gener. & management sys.		🟦		🟦	🟦																													🟦	🟦	🟦	🟦	🟦										
	Thermal control system		🟦			🟦	🟦																	🟦	🟦																								
	Data handling system	🟦	🟦		🟦	🟦	🟦				🟦															🟦																							
	Communication system	🟦	🟦		🟦	🟦			🟦	🟦	🟦																																🟦						
	Crew support system		🟦		🟦	🟦																																		🟦	🟥	🟥	🟦				🟦	🟦	🟦
Transportation module	Atmosphere containment system		🟦			🟦																🟦																										
	Environmental control system		🟦		🟦	🟦																		🟦	🟦																	🟦				🟦	🟦	🟦	🟦
	Environmental protection		🟦			🟦																🟦	🟥	🟥	🟦																			🟦	🟦				
	Structure & mechanisms		🟦			🟦											🟦	🟦		🟦		🟦					🟦		🟦		🟦													🟦					
	Electr.l power gener. & management sys.		🟦		🟦	🟦																													🟦	🟦	🟦	🟦	🟦										
	Thermal control system		🟦			🟦	🟦																🟦	🟥	🟦																								
	Data handling system	🟦	🟦		🟦	🟦	🟦				🟦															🟦																							
	Communication system	🟦	🟦		🟦	🟦			🟦		🟦																																🟦						
	Crew support system		🟦		🟦	🟦																																		🟦	🟦	🟦					🟦	🟦	🟦
	ADCS		🟦			🟦	🟦						🟦	🟦	🟦	🟥																	🟦															
	Guidance and navigation system		🟦		🟦	🟦		🟦				🟦	🟦	🟦	🟦	🟥													🟦																			
	Propulsion system		🟦			🟦								🟥				🟦														🟦	🟥	🟦														
	Entry and landing system		🟦			🟦		🟦	🟦		🟦	🟦	🟦		🟥			🟦				🟦	🟥	🟦	🟦			🟦	🟦			🟦	🟦	🟦									🟦						
Robotic Infrastructure	Environmental protection		🟦			🟦													🟦																									🟦	🟦				
	Structure & mechanisms		🟦			🟦													🟦	🟦							🟦	🟦	🟦	🟦														🟦					
	Electr.l power gener. & management sys.		🟦			🟦													🟦																🟦		🟦		🟦										
	Thermal control system		🟦			🟦																			🟦																							
	Data handling system	🟦	🟦		🟦	🟦					🟦															🟦																							
	Communication system	🟦	🟦			🟦			🟦	🟥	🟦																																🟦						
	Observation system		🟦		🟦	🟦	🟦	🟦	🟦				🟦																																			
	Mobility system		🟦		🟦	🟦						🟦	🟥														🟦	🟥	🟦	🟥																		
	Digging & Grabbing system		🟦	🟦	🟦	🟦							🟦						🟦								🟦	🟦	🟦	🟦																🟦			
ISRU Infrastructure	Environmental protection		🟦	🟦		🟦															🟦																							🟦	🟦				
	Structure & mechanisms		🟦	🟦		🟦													🟦	🟦	🟦						🟦		🟦	🟦														🟦					
	Electr.l power gener. & management sys.		🟦	🟦	🟦	🟦																													🟦	🟦	🟥	🟦	🟦										
	Thermal control system		🟦	🟦		🟦																			🟦																							
	Data handling system	🟦	🟦	🟦	🟦	🟦					🟦															🟦																							
	Communication system	🟦	🟦	🟦	🟦	🟦			🟦		🟦																																🟦						
	Resources extraction system		🟦	🟦	🟦	🟦																								🟥		🟦																	
Spacecraft	Environmental protection		🟦			🟦																🟦																						🟦	🟦				
	Structure & mechanisms		🟦			🟦											🟦			🟦		🟦					🟦	🟦	🟦		🟦													🟦					
	Electr.l power gener. & management sys.		🟦			🟦																													🟦		🟦	🟦	🟦										
	Thermal control system		🟦			🟦	🟦																		🟦																							
	Data handling system	🟦	🟦			🟦	🟦				🟦															🟦																							
	Communication system	🟦	🟦			🟦			🟦		🟦																																🟦						
	ADCS		🟦			🟦	🟦									🟦																	🟦															
	Guidance and navigation system		🟦			🟦		🟦				🟦				🟦													🟦																			
	Observation system		🟦			🟦	🟦	🟦	🟦				🟦																																			

Figure 25: Applicability Analysis between the second level of BBs (the first one is in bold type) and TAs (in bold type) and Technology Subject (i.e. the second level of TAs).



Building Blocks		Habitable module									Transportation module													Robotic infrastructure									ISRU infrastructure							Spacecraft								
Mission Concepts		Atmosphere containment system	Environmental control system	Environmental protection	Structure & mechanisms	Electr. power generation & management sys.	Thermal control system	Data handling system	Communication system	Crew support system	Atmosphere containment system	Environmental control system	Environmental protection	Structure & mechanisms	Electr. power generation & management sys.	Thermal control system	Data handling system	Communication system	Crew support system	Attitude determination and control system	Guidance and navigation system	Propulsion system	Entry and landing system	Environmental protection	Structure & mechanisms	Electr. power generation & management sys.	Thermal control system	Data handling system	Communication system	Observation system	Mobility system	Digging & Grabbing system	Environmental protection	Structure & mechanisms	Electr. power generation & management sys.	Thermal control system	Data handling system	Communication system	Resources extraction system	Environmental protection	Structure & mechanisms	Electr. power generation & management sys.	Thermal control system	Data handling system	Communication system	Attitude determination and control system	Guidance and navigation system	Observation system
Earth	*Theoretical principles formulation*	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Analytical proof	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Experimental proof	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Laboratory components/breadboard	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Components/breadboard valid. in not controlled	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Sys./subs. prototype demo. in not controlled environ.	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
LEO	*Components/breadboard validation*	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	System/subsystem prototype demonstration	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Complete system flight qualification	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	LEO Exploitation - permanent station (ISS, post-ISS Station)	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	🟦	🟦	⬜	⬜	🟦	🟦	⬜	🟦	🟦	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦
	1st MPCV Unmanned Demonstration Mission	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬜	🟦	🟦	⬜	🟦	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	2nd Manned MPCV Manned Demonstration Mission	🟦	🟦	🟦	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬜	🟦	🟦	⬜	🟦	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	LEO Exploitation - Free flyers (e.g. Dragon, Dreamchaser)	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬜	🟦	🟦	⬜	🟦	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Follow-on MPCV Missions	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Moon	Luna-Resours-Lander	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	⬜	🟦	🟦	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Lunar Polar Sample Return	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Extended crew duration missions in cis-lunar space	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Human-lunar surface missions	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Human-robotic Partnership Missions	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Human Assisted Sample Return	🟦	🟦	🟦	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Mars	ExoMars 2016	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	ExoMars 2018	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Post ExoMars mission	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	MSR preparation / MSR elements	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Enabling long term technology	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Human Mars	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

Figure 26: Applicability Analysis between the second level of BBs and MCs.
A blue cell means an existing link, while white cells a missing link.

Finally, considering applicability maps between elements of the same type, a particular analysis is required: *applicability of technologies onto technologies*. A similar map, allows the definition of technologies' compatibility to assess the possibility of integrating different technologies within the same BB. 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. This kind of knowledge can only be acquired by people used to work with the technologies analysed. It has to be said that parameters such as IRL can provide a draft estimation also remembering that at this point data about where two different technologies are required together (i.e. in the same BB) are known. Comparing TRL, IRL and applicability labels definitions is, therefore, possible to propose a draft estimation of the integration capability between two different technologies. Figure 27 depicts an example of applicability map between technologies (i.e. TAs at the third level).

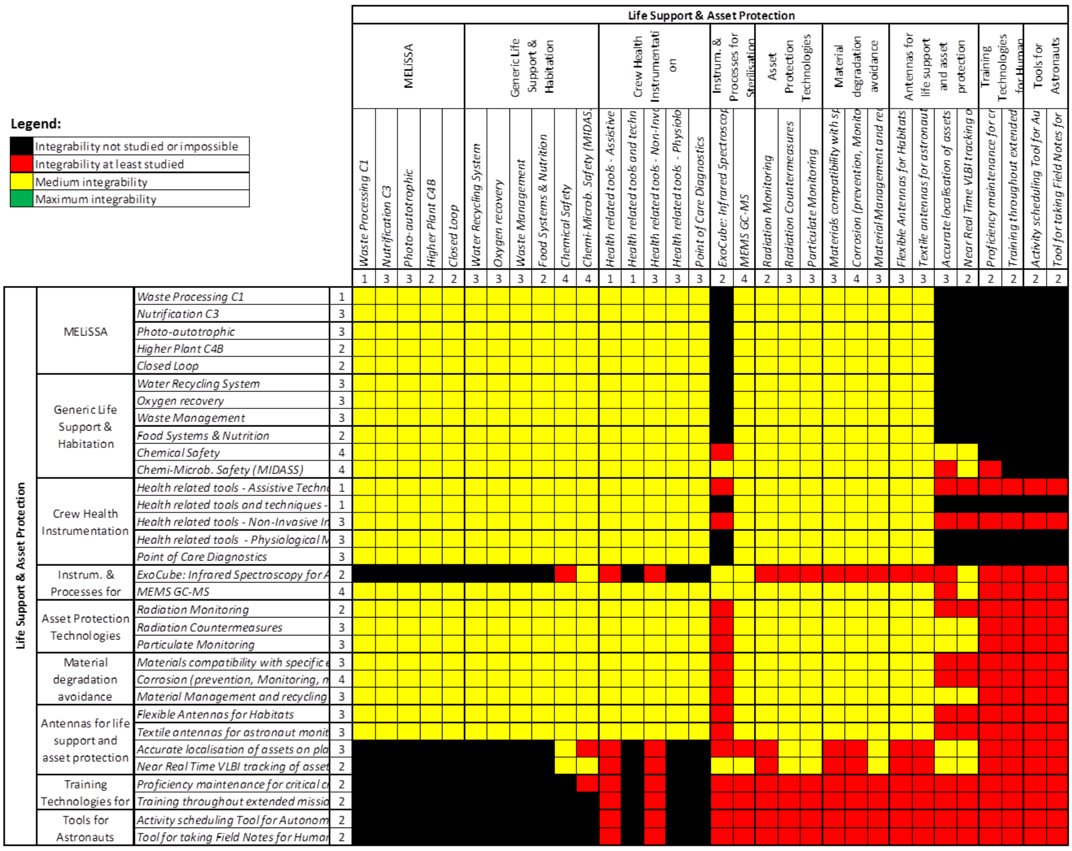


Figure 27: Applicability Analysis of technologies onto technologies.

It has to be said that, having proposed the applicability maps definition based on Functional Analysis, every group of roadmap element can be related with itself and with the other groups. Another example of Applicability Analysis can be provided analysing the same Functional Analysis that has led to the update of (ESA, 2015b) explained in (Saccoccia, 2017). The update of this particular roadmap is based on a Functional Analysis (Figure 28) and from the top level function describing the whole SoS, different levels of products can be derived: segments (i.e. space and ground segments), BBs (i.e. at the same level OCs are derived before), TAs and subjects (i.e. the same listed in (ESA, 2015b)). As already said, the update of the elements of an existing roadmap is the objective of this example and, for this reason, different applicability maps are there significant, such as the applicability of OCs on MCs (Figure 29).

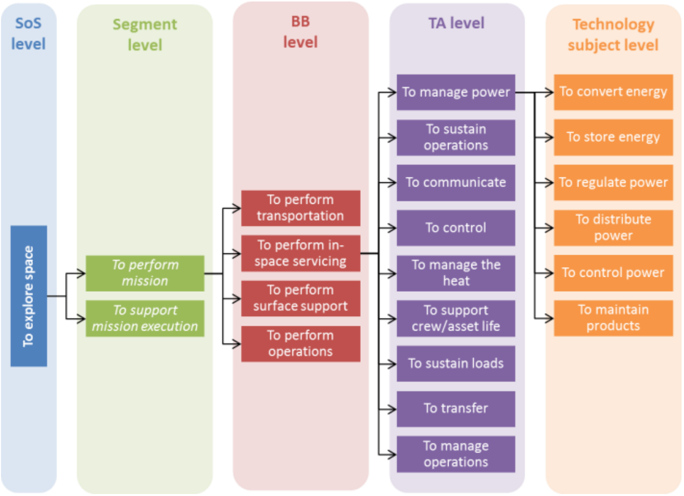


Figure 28: Example of Functional Analysis.

Hypothetical Mission Concepts / Functional Capabilities	Short permanently inhabited mission from Earth to LEO	Long permanently inhabited mission from Earth to LEO	Short man-tended mission from Earth to LEO	Long man-tended mission from Earth to LEO	Short robotic mission from Earth to LEO	Long robotic mission from Earth to LEO	Short permanently inhabited mission from Moon Vicinity to LEO	Long permanently inhabited mission from Moon Vicinity to LEO	Short man-tended mission from Moon Vicinity to LEO	Long man-tended mission from Moon Vicinity to LEO	Short robotic mission from Moon Vicinity to LEO	Long robotic mission from Moon Vicinity to LEO
High performance human transfer	🟥	🟥	🟥	🟥			🟥	🟥	🟥	🟥		
High capacity cargo transfer	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Orbit maintenance (Cargo)	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Orbit maintenance (Human)	🟥	🟥	🟥	🟥			🟥	🟥	🟥	🟥		
Cargo entry	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Manned entry	🟥	🟥	🟥	🟥			🟥	🟥	🟥	🟥		
Surface high precision cargo D&L												
Surface high precision cargo Descent & Impact												
Surface high precision manned D&L												
Manned take-off/lift-off and ascent	🟥	🟥	🟥	🟥								
Cargo take-off/lift-off and ascent	🟥	🟥	🟥	🟥	🟥	🟥						
In space multiple element assembly	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Communications (high DR)	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Low-g bodies anchoring												
Sample analysis and containment												
Robotic tele-operations	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
In-Space fuel management	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
In-Space long term fuel storage	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
In-Space high capacity power generation and management	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
In-Space life support	🟥	🟥	🟥	🟥			🟥	🟥	🟥	🟥		
In-Space short-term human habitability	🟥	🟥	🟥	🟥			🟥	🟥	🟥	🟥		
In-Space long-term human habitability	🟥	🟥	🟥	🟥			🟥	🟥	🟥	🟥		
In-Space radiation protection												
In-Space autonomous supporting robotics	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
In-Space IVA, EVA, IEVA	🟥	🟥	🟥	🟥			🟥	🟥	🟥	🟥		
In-space interface EVA	🟥	🟥	🟥	🟥			🟥	🟥	🟥	🟥		
Surface multiple element assembly												
Surface high capacity power generation and management												
Surface life support												
Surface short-term human habitability												
Surface long-term human habitability												
Surface radiation protection												
Surface robotics												
ISRU												
Surface long term fuel storage												
Surface high capacity fuel management												
Surface IVA, EVA, IEVA												
Surface interface EVA												
Low-g bodies human surface mobility												
Low-g bodies cargo surface mobility												

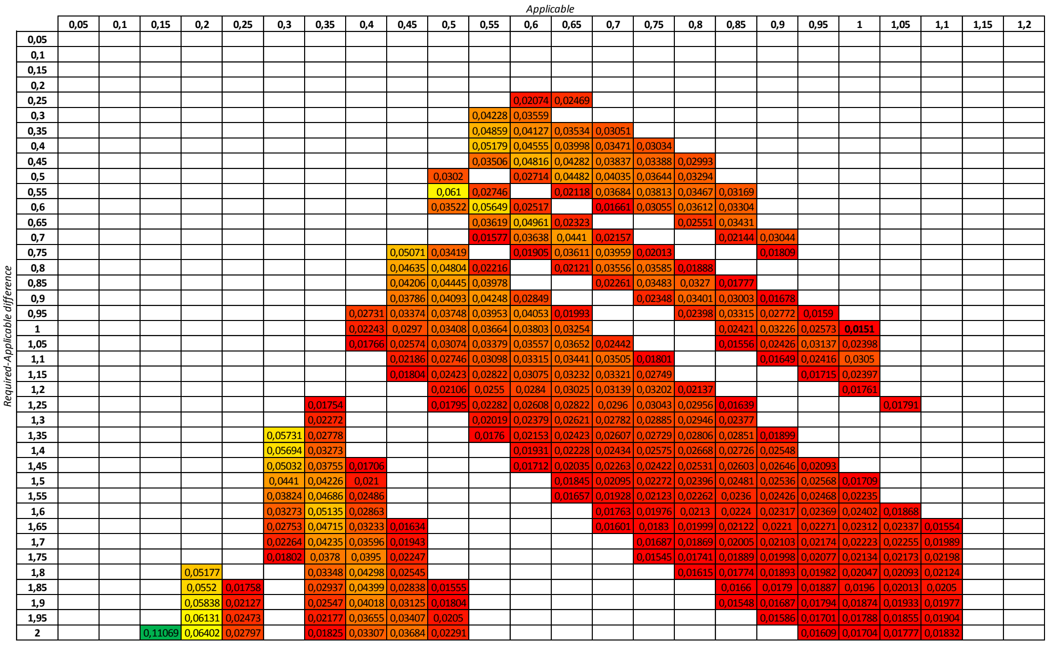
Figure 29: Example of Applicability Analysis of OCs on MCs.
A red cell means an existing link, while white cells a missing link. Only some hypothetical MCs are listed, between Earth or Moon vicinity and LEO.

2.3.3. Sensitivity Analysis

Having mapped the various groups of elements between them and having sized the reciprocal links according to a set of labels, in order to provide rational choices it is required to weight the reciprocal link importance and optimize the results obtained based on market and stakeholders' needs. To do so, a sensitivity analysis can be proposed. In particular, some parameters can steam out from the Applicability Analysis to be a support for the next phases and some of them are strictly related to possible labels weights. In particular, the following parameters can be considered: *pseudo-TRL*, the sum of the different weights related to a single technology over the different OCs (*most required/applicable between the OCs*) and the sum of the different weights related to a single technology over the different BBs (*most required/applicable between the BBs*).

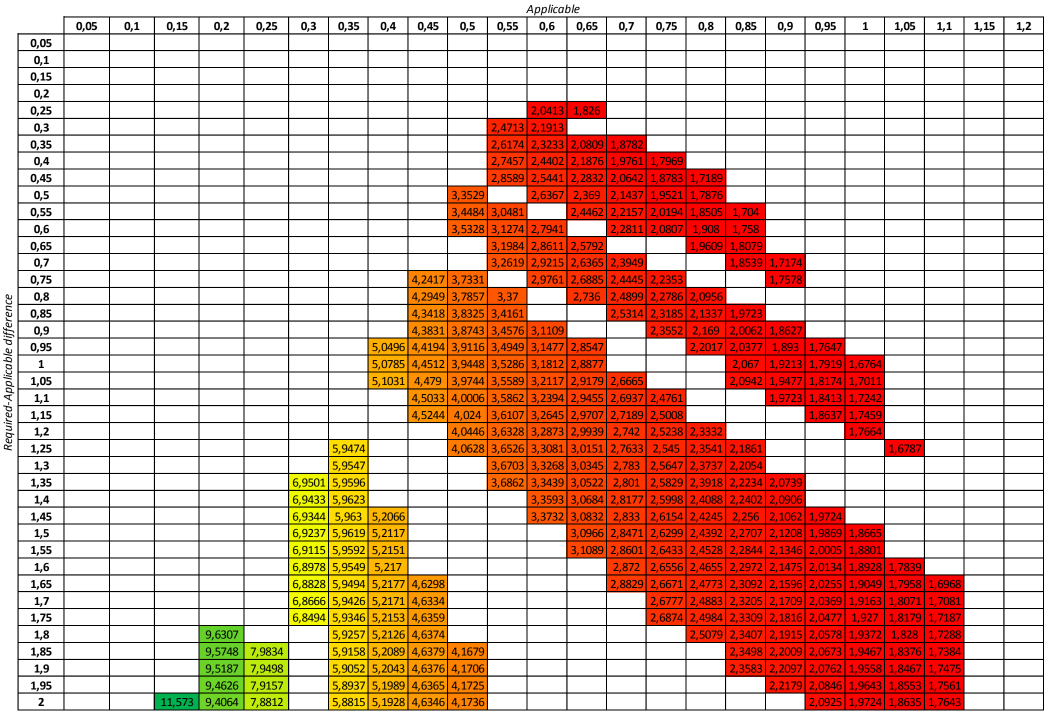
These parameters are related to a quantification of how much a specific technology can be required or applicable to other types of elements. The focus of the last two parameters is on the technologies, being the technologies the basic element for the roadmap definition, but different focuses can be proposed (e.g. defining how an OCs can be required/applicable between the different technologies). Using as reference the applicability maps achieved in the previous sections it is possible to evaluate all these parameters. While for the first attempt of pseudo-TRL weights where imposed (e.g. weight a_j equal to 1.00 for "applicable" combinations, weight r_i equal to 2.00 for "required" combinations and 0 for "not applicable" combinations), in performing a sensitivity analysis these weights have to be varied to see what happens to the previously listed three parameters. The only weight that can be fixed is the "not applicable" one (i.e. 0).

For example, in order to optimize the one of the three parameters, a used might be interested in branching out the different pseudo-TRL of the different OCs. Indeed, in applying the weight proposed before the minimum difference between these values is of about 0.02, while the maximum difference is of about 1.68. If every combinations of weights is applied to the applicability maps, varying both the "applicable" weight and the difference between this weight and the "required" one between 0 not included and 2 included (with a step of 0.05 for simplicity), it is possible to find how the minimum and the maximum differences between pseudo-TRL values varies. In addition, constraints over the other two parameters can be supposed. For example, it can be supposed that these values have to change only between ±50%. Figure 30 and Figure 31 shows the results of this analysis, plotting the minimum and maximum pseudo-TRL values differences that respect the constraints and that are at least equal to the current status.



Required-Applicable difference	Applicable																							
	0,05	0,1	0,15	0,2	0,25	0,3	0,35	0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8	0,85	0,9	0,95	1	1,05	1,1	1,15	1,2
0,05																								
0,1																								
0,15																								
0,2																								
0,25												0,02074	0,02469											
0,3											0,04228	0,03559												
0,35											0,04859	0,04127	0,03534	0,03051										
0,4											0,05179	0,04555	0,03998	0,03471	0,03034									
0,45											0,03506	0,04816	0,04282	0,03837	0,03388	0,02993								
0,5										0,0302		0,02714	0,04482	0,04035	0,03644	0,03294								
0,55										0,061	0,02746		0,02118	0,03684	0,03813	0,03467	0,03169							
0,6										0,03522	0,05649	0,02517		0,01661	0,03055	0,03612	0,03304							
0,65											0,03619	0,04961	0,02323			0,02551	0,03431							
0,7											0,01577	0,03638	0,0441	0,02157			0,02144	0,03044						
0,75									0,05071	0,03419		0,01905	0,03611	0,03959	0,02013			0,01809						
0,8									0,04635	0,04804	0,02216		0,02121	0,03556	0,03585	0,01888								
0,85									0,04206	0,04445	0,03978			0,02261	0,03483	0,0327	0,01777							
0,9									0,03786	0,04093	0,04248	0,02849			0,02348	0,03401	0,03003	0,01678						
0,95								0,02731	0,03374	0,03748	0,03953	0,04053	0,01993			0,02398	0,03315	0,02772	0,0159					
1								0,02243	0,0297	0,03408	0,03664	0,03803	0,03254				0,02421	0,03226	0,02573	**0,0151**				
1,05								0,01766	0,02574	0,03074	0,03379	0,03557	0,03652	0,02442			0,01556	0,02426	0,03137	0,02398				
1,1									0,02186	0,02746	0,03098	0,03315	0,03441	0,03505	0,01801			0,01649	0,02416	0,0305				
1,15									0,01804	0,02423	0,02822	0,03075	0,03232	0,03321	0,02749				0,01715	0,02397				
1,2										0,02106	0,0255	0,0284	0,03025	0,03139	0,03202	0,02137				0,01761				
1,25							0,01754			0,01795	0,02282	0,02608	0,02822	0,0296	0,03043	0,02956	0,01639				0,01791			
1,3							0,02272				0,02019	0,02379	0,02621	0,02782	0,02885	0,02946	0,02377							
1,35						0,05731	0,02778				0,0176	0,02153	0,02423	0,02607	0,02729	0,02806	0,02851	0,01899						
1,4						0,05694	0,03273					0,01931	0,02228	0,02434	0,02575	0,02668	0,02726	0,02548						
1,45						0,05032	0,03755	0,01706				0,01712	0,02035	0,02263	0,02422	0,02531	0,02603	0,02646	0,02093					
1,5						0,0441	0,04226	0,021					0,01845	0,02095	0,02272	0,02396	0,02481	0,02536	0,02568	0,01709				
1,55						0,03824	0,04686	0,02486					0,01657	0,01928	0,02123	0,02262	0,0236	0,02426	0,02468	0,02235				
1,6						0,03273	0,05135	0,02863						0,01763	0,01976	0,0213	0,0224	0,02317	0,02369	0,02402	0,01868			
1,65						0,02753	0,04715	0,03233	0,01634					0,01601	0,0183	0,01999	0,02122	0,0221	0,02271	0,02312	0,02337	0,01554		
1,7						0,02264	0,04235	0,03596	0,01943						0,01687	0,01869	0,02005	0,02103	0,02174	0,02223	0,02255	0,01989		
1,75						0,01802	0,0378	0,0395	0,02247						0,01545	0,01741	0,01889	0,01998	0,02077	0,02134	0,02173	0,02198		
1,8				0,05177			0,03348	0,04298	0,02545							0,01615	0,01774	0,01893	0,01982	0,02047	0,02093	0,02124		
1,85				0,0552	0,01758		0,02937	0,04399	0,02838	0,01555							0,0166	0,0179	0,01887	0,0196	0,02013	0,0205		
1,9				0,05838	0,02127		0,02547	0,04018	0,03125	0,01804							0,01548	0,01687	0,01794	0,01874	0,01933	0,01977		
1,95				0,06131	0,02473		0,02177	0,03655	0,03407	0,0205								0,01586	0,01701	0,01788	0,01855	0,01904		
2			0,11069	0,06402	0,02797		0,01825	0,03307	0,03684	0,02291									0,01609	0,01704	0,01777	0,01832		

Figure 30: Map of the minimum pseudo-TRL values differences.



Required-Applicable difference	Applicable																							
	0,05	0,1	0,15	0,2	0,25	0,3	0,35	0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8	0,85	0,9	0,95	1	1,05	1,1	1,15	1,2
0,05																								
0,1																								
0,15																								
0,2																								
0,25												2,0413	1,826											
0,3											2,4713	2,1913												
0,35											2,6174	2,3233	2,0809	1,8782										
0,4											2,7457	2,4402	2,1876	1,9761	1,7969									
0,45											2,8589	2,5441	2,2832	2,0642	1,8783	1,7189								
0,5										3,3529		2,6367	2,369	2,1437	1,9521	1,7876								
0,55										3,4484	3,0481		2,4462	2,2157	2,0194	1,8505	1,704							
0,6										3,5328	3,1274	2,7941		2,2811	2,0807	1,908	1,758							
0,65											3,1984	2,8611	2,5792			1,9609	1,8079							
0,7											3,2619	2,9215	2,6365	2,3949			1,8539	1,7174						
0,75									4,2417	3,7331		2,9761	2,6885	2,4445	2,2353			1,7578						
0,8									4,2949	3,7857	3,37		2,736	2,4899	2,2786	2,0956								
0,85									4,3418	3,8325	3,4161			2,5314	2,3185	2,1337	1,9723							
0,9									4,3831	3,8743	3,4576	3,1109			2,3552	2,169	2,0062	1,8627						
0,95								5,0496	4,4194	3,9116	3,4949	3,1477	2,8547			2,2017	2,0377	1,893	1,7647					
1								5,0785	4,4512	3,9448	3,5286	3,1812	2,8877				2,067	1,9213	1,7919	1,6764				
1,05								5,1031	4,479	3,9744	3,5589	3,2117	2,9179	2,6665			2,0942	1,9477	1,8174	1,7011				
1,1									4,5033	4,0006	3,5862	3,2394	2,9455	2,6937	2,4761			1,9723	1,8413	1,7242				
1,15									4,5244	4,024	3,6107	3,2645	2,9707	2,7189	2,5008				1,8637	1,7459				
1,2										4,0446	3,6328	3,2873	2,9939	2,742	2,5238	2,3332				1,7664				
1,25							5,9474			4,0628	3,6526	3,3081	3,0151	2,7633	2,545	2,3541	2,1861				1,6787			
1,3							5,9547				3,6703	3,3268	3,0345	2,783	2,5647	2,3737	2,2054							
1,35						6,9501	5,9596				3,6862	3,3439	3,0522	2,801	2,5829	2,3918	2,2234	2,0739						
1,4						6,9433	5,9623					3,3593	3,0684	2,8177	2,5998	2,4088	2,2402	2,0906						
1,45						6,9344	5,963	5,2066				3,3732	3,0832	2,833	2,6154	2,4245	2,256	2,1062	1,9724					
1,5						6,9237	5,9619	5,2117					3,0966	2,8471	2,6299	2,4392	2,2707	2,1208	1,9869	1,8665				
1,55						6,9115	5,9592	5,2151					3,1089	2,8601	2,6433	2,4528	2,2844	2,1346	2,0005	1,8801				
1,6						6,8978	5,9549	5,217						2,872	2,6556	2,4655	2,2972	2,1475	2,0134	1,8928	1,7839			
1,65						6,8828	5,9494	5,2177	4,6298					2,8829	2,6671	2,4773	2,3092	2,1596	2,0255	1,9049	1,7958	1,6968		
1,7						6,8666	5,9426	5,2171	4,6334						2,6777	2,4883	2,3205	2,1709	2,0369	1,9163	1,8071	1,7081		
1,75						6,8494	5,9346	5,2153	4,6359						2,6874	2,4984	2,3309	2,1816	2,0477	1,927	1,8179	1,7187		
1,8				9,6307			5,9257	5,2126	4,6374							2,5079	2,3407	2,1915	2,0578	1,9372	1,828	1,7288		
1,85				9,5748	7,9834		5,9158	5,2089	4,6379	4,1679							2,3498	2,2009	2,0673	1,9467	1,8376	1,7384		
1,9				9,5187	7,9498		5,9052	5,2043	4,6376	4,1706							2,3583	2,2097	2,0762	1,9558	1,8467	1,7475		
1,95				9,4626	7,9157		5,8937	5,1989	4,6365	4,1725								2,2179	2,0846	1,9643	1,8553	1,7561		
2			11,573	9,4064	7,8812		5,8815	5,1928	4,6346	4,1736									2,0925	1,9724	1,8635	1,7643		

Figure 31: Map of the maximum pseudo-TRL values differences.

In this particular example, a set of weights that maximises both the minimum and the maximum difference between the pseudo-TRL values is 0.15 for the “applicable” weight and 2.15 for the “required” weight. Thanks to this computation the pseudo-TRL changes:

- Human Surface Habitability and Operations: from 1.32 to 1.22;
- Robotic/Tele-robotic Surface Operations: from 2.39 to 4.22;
- Interoperability: from 2.96 to 12.80;
- Nuclear Energy utilisation: from 2.99 to 12.34;
- (Fast) Sustainable Human Flight and Cruise: from 1.43 to 1.33;
- Precision Soft Landing (with Hazard Avoidance): from 2.35 to 4.05;
- ISRU: from 2.75 to 6.00;
- In-orbit refuelling: from 2.71 to 7.36;
- Efficient Orbit Insertion and Maintenance: from 2.77 to 8.22;
- Entry, Deceleration and Descent (Earth, targets): from 2.31 to 3.81;
- High Capacity Cargo Transfer: from 2.47 to 4.79;
- RdV and Docking with (non) collaborative target: from 2.56 to 5.51;
- Surface Ascent and Return (Robotic / Human): from 2.63 to 6.11.

From this list it can be seen that, even if the exercise proposed in the previous section was not related to the enhancement of all the capabilities, an advancement in a group of technologies can have a significant effect on the entire set of capabilities. Indeed, where the pseudo-TRL increase this means an enhancement in the specific OC.

The final minimum difference between the values is of about 0.11 and the maximum difference is of about 11.57. It has to be said that only one parameter has been optimized applying the other as constraints. A better solution might be finding sub-optimal set of weights able to branch out the three parameters.

2.3.4. Prioritization Studies

At this point roadmaps elements, their features and their reciprocal relationships are clear. In order to proceed with the planning with a semi-automatic procedure, some data are required. For example, at this point of the analysis also the main strategies that the stakeholders have are known. These strategies are related to the directions that the stakeholders would have favoured in defining the roadmap. If a translation of these criteria to quantitative parameters is possible, these criteria can be used to order the roadmaps elements and suggest directions. It has to be said that usually, stakeholders in space exploration projects are more interested in providing criteria on technologies and it can be easy to define ad-hoc prioritization method for the other elements not relating them to stakeholders.

In literature, many methods for prioritization activities are available and some of them are based on the modelling and simulation of physical and economic processes and other on stakeholders' criteria to compare the different alternatives. All these methods apply objective tools and criteria together with subjective human beings involved in the prioritization loop. These prioritization methods derives from Decision Analysis, as, for example, AHP, Decision Trees (McNamee, 2001), Multi-voting Technique, Strategy Grids, Nominal Group Techniques, the Hanlon Method and Prioritization Matrix (McNamee, 2001; NACCHO, 2010; Charania, 2001).

It has to be said that employing an objective prioritization technique can reduce the uncertainties in the prioritization problem providing a structured mechanism for the roadmap elements ranking. This is the main problem, for example of the Nominal Group Technique that needs a high interaction with stakeholders. Looking at another example, the Multi-voting Technique is useful when exclusions have to be made, but the aim of this phase is to define an ordered list of elements. Also the Strategy Grid has to be excluded, being highly probable to deal with more than two criteria. In addition, even if the Hanlon Method is a mathematical process, is not easy to adapt it to a different type and number of criteria different from the ones for which it has been created. On the contrary, the Prioritization Matrix (or decision matrix), AHP and Decision Trees provide visual methods that can be combined and readapted to achieve the current phase purposes. A method that can be proposed can be a hybrid version of these ones. Certainly, defining the criteria starting from stakeholders' needs, a certain level of subjectivity has to be imagined. A decision tree approach can be applied to achieve every possible combination of the proposed criteria (all or part of them) and a trade-off analysis similar to a prioritization matrix approach can be proposed to study these criteria according to rational data, is a useful way to guarantee optimal results.

2.3.4.1. Technologies prioritization: process

Starting from HERACLES mission and focusing on technologies prioritization, possible examples of criteria are "*To enhance technologies with low TRL*" (i.e. to develop not studied technologies) and "*To enhance technologies that are most required/applicable between the BBs*" (i.e. higher reusability). In applying these criteria, technologies are ordered according to the most required/applicable ones according with the Applicability Analysis performed on (ESA, 2015b): to this purpose required and applicable technologies can be counted making used of the previously defined weights (r_i and a_j) so that required technologies count more than applicable ones. Then, if one or more technologies achieve the same value in the ranking, these technologies will be ranked according to TRL in ascending order. The ranking procedure described above has as benefit to ensure that the most required technologies are addressed first and that TRL increase of the most applicable (and required) technologies will be considered before. In addition, applying the criteria in this order and with this process is possible to limit the criteria weights for the prioritization matrix at this only order. In this way, it is possible to reduce the number of variables that have an influence on the result.

If Stakeholders' Analysis and interviews are considered, list possible criteria according to the six influence areas listed before probably will include more than two criteria (Table 7). For example, if the stakeholder requires the following criteria for the prioritization, a method has to be proposed:

1. *To enhance technologies that are most required/applicable between the OCs* (hereafter called criterion #1, for simplicity);
2. *To enhance technologies that are most required/applicable between the BBs* (hereafter called criterion #2);
3. *To enhance technologies with low TRL* (hereafter called criterion #3);
4. *End the development of advanced techs* (i.e. to enhance technologies with high TRL, hereafter called criterion #4).

If the idea is to apply the same procedure described before, the presence of multiple criteria implies the application of these criteria in a specific order. The order of the criteria can be supposed analysing different combinations of them. Combining the chosen criteria, 120 possible combinations are foreseen (see (Cresto Aleina, 2017e; Saccoccia, 2015) for details), but only 27 of them are possible (for the incompatibility of the two criteria related to the TRL). These 27 combinations are then used to order the list of technologies. For simplicity, only 2 BBs of high relevance for HERACLES will be considered: "*Tele-robotic and autonomous control systems*" and "*Storable propulsion modules and equipment*" BBs. Limiting the list of technologies to the ones applicable or required on these BBs is possible to obtain 27 different ordered lists.

Usually, in applying the Decision Tree method a value (e.g. a probability) is used to weight the different branches. A possible value can be derived from risk analysis, having enough data about the technologies involved. Indeed, it is possible to use the total probability of failure and other values coming from this analysis. Defining these values means being able to perform a trade-off analysis between the different criteria combinations. Each value can be considered a Figures of Merit (FoM) and used to compare the different possibilities. For this purpose, the following three FoMs are considered: TRL cost-effectiveness (FoM_1), average costs increase (FoM_2) and total probability of failure (FoM_3). The second and the third FoMs are defined through a risk analysis in an iterative process (i.e. assumed at the worst conditions at the first iteration and revised in defining the roadmap) and for their definition process refer to (Cresto Aleina, 2017e; Saccoccia, 2015). On the contrary, the first FoM is the simpler to define, considering a group of technologies (i):

$$FoM_1 = \frac{\sum_i \Delta TRL_i}{\sum_i \Delta costs_i} \tag{2.2}$$

(ESA, 2015b) and statistical analysis can be used to have additional information about the three FoMs. It has to be noticed that FoM_1 has lower values where the production of the first sub-systems or devices starts (Figure 32). In addition to this, being this value based on assumptions and a statistical analysis, high values of probability of failures will be accepted and considered as a sort of warning: no exclusion will be made on this basis not being sure of the level of approximation applied. It has to be said that if the FoMs are evaluated for every combinations over the entire list of technologies, this analysis will be useless: it is important to limit the FoMs evaluation to a partial group of entire list of ordered technologies, or in other words to impose a maximum number of technologies on which evaluate the FoMs. A sensitivity analysis has been performed to find how this limit can influence the result (Figure 33) and choose the number of technologies on which define the three FoMs.

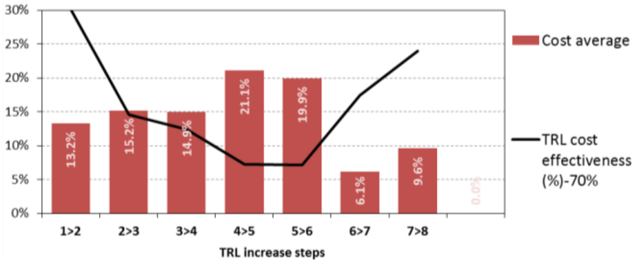


Figure 32: Cost average and TRL costs effectiveness based on (ESA, 2015b).

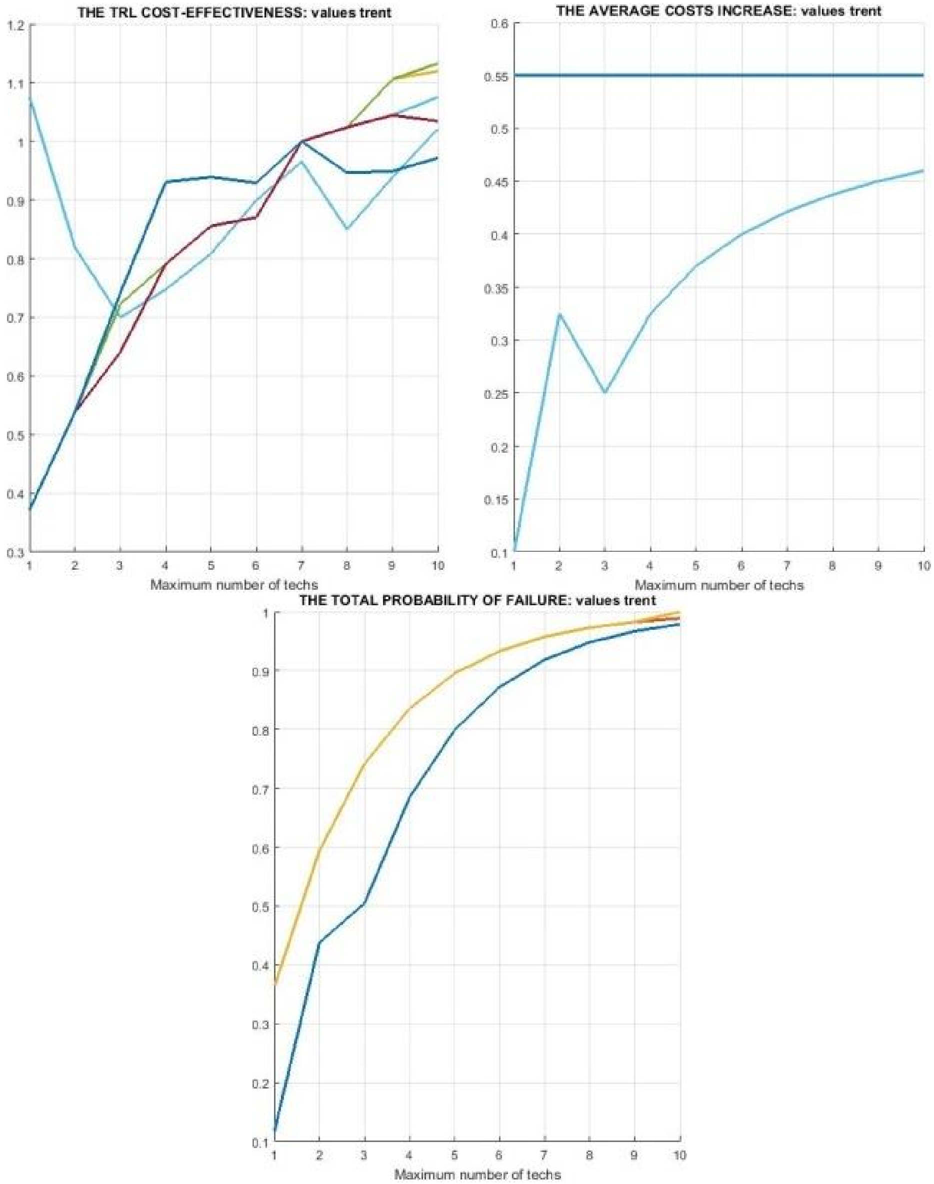


Figure 33: Sensitivity analysis results.
Different colours means different criteria combinations.

For example, it is possible to have a high number of technologies to limit the evaluation of the FoMs. In HERACLES application, this situation leads to a higher differentiation of results for the FoMs, but leads also to total probabilities of failures really near to 1. On the contrary, choosing a lower number of technologies is possible to have a lower differentiation of results for the FoMs, but total probabilities of failures different from 1. Being the case in which the total probability of failure is quite 1 a condition in which no difference can be appreciated, only 3 technologies will be considered for the FoMs evaluation. This choice is in line also with the amount of resources that can be related to a mission whose BBs are not currently under production.

In defining a process able to choose automatically between the difference criteria combinations, it is possible to study a way to combine the three FoMs in a unique parameter. Two rules can be proposed:

$$TOT1 = \frac{FoM1(1 - FoM3)}{FoM2} \tag{2.3}$$

$$TOT2 = k1 \cdot FoM1 - k2 \cdot FoM2 + k3 \cdot (1 - FoM3) \tag{2.4}$$

Where $k1$, $k2$ and $k3$ are coefficients in $\mathbb{R}$, defined assuming that:

$$k1 > k2 \text{ and } k1 > k3 \tag{2.5}$$

$$k1, k2 \text{ and } k3 > 0 \tag{2.6}$$

$$k1 + k2 + k3 = 1 \tag{2.7}$$

While in the first method the FoMs are combined considering if their increase will make the list better or worst in achieving the optimal solution, in the second method the FoMs are combined using weights with an approach more similar to a prioritization matrix. It has to be said that for the second rule, 1601 possible combinations of coefficients are achieved, even if all these combinations give quite the same results: indeed, criterion #4 is the one that by itself can lead to an optimal result (Table 10). Being the results achieved similar and being the first rule simpler to be applied and modified, (2.3) has to be preferred. Additionally, none of the two rules relate with the stakeholder asking for each criteria: a coefficient able to weight this aspect will have to be proposed.

Looking at the results can be seen that no correspondence exists between these results and the stakeholders' relevance and, for this reason, a corrective coefficient will have to be proposed. In addition, it has to be said that a similar approach can be also simplified to achieve a first qualitative prioritization of technologies. For example, it can be imagined to apply at every criterion a sort of filter to see if a specific stakeholder can consider each technology as enabling, enhancing or not important. A similar analysis can support the definition of applicable, required and not important labels in the applicability maps.

Table 10: Criteria combinations ranking according to the two evaluation methods.

	Criteria combinations																									
	1	*1>2*	*1>2>3*	*1>2>4*	*1>3*	*1>3>2*	*1>4*	*1>4>2*	*2*	*2>1*	*2>1>3*	*2>1>4*	*2>3*	*2>3>1*	*2>4*	*2>4>1*	*3*	*3>1*	*3>1>2*	*3>2*	*3>2>1*	***4***	*4>1*	*4>1>2*	*4>2*	*4>2>1*
TOT 1	6	6	5	6	5	5	6	6	4	4	4	4	3	3	4	4	2	2	2	2	2	**1**	7	7	7	7
TOT 2	9	9	8	9	8	8	9	9	7	7	7	7	5/6	5/6	7	7	3	3	3	3	3	**1/2**	5/6	1/2	4	4

2.3.4.2. Technologies prioritization: real case comparison

As previously explained, a traditional roadmapping process is based on interactions with stakeholders, trough workshops and interviews. This is true also for a prioritization process. An example is the process started at the beginning of 2016 at ESA to define technology priorities for space exploration, led by the Directorate for Human Spaceflight and Robotic Exploration and supported by the Directorates of Technical and Quality Management and of Operations (ESA, 2016) in cooperation with ESA Member States representatives. The prioritization exercise was focused on 32 technologies, preselected between the technologies critical to enable strategic missions or to assure a sustained role to European industries (Table 11).

Thanks to a workshop between ESA Member States, technology priorities have been defined based on some suggested criteria, suggested by ESA to the ESA Member States representatives:

1. *To guarantee a role for Europe in the future space exploration scenario*, focusing on the technologies that fill identified gap at international level;
2. *To require ISS (International Space Station)demonstration*, focusing on the technologies that need ISS for validation purposes;
3. *To not require unique ground validation programmes*, focusing on the technologies that do not need specific and unique ground validation programmes;
4. *To minimize affordability/programmatic aspects*, considers affordability (e.g. CaC vs. Available Budget) and programmatic

aspects (e.g. planned TRL progression vs. missions development and launch date);

5. *To guarantee non-space application*, potential application of technology to other space and non-space fields identified.

While in (ESA, 2016) all the data to size these criteria and the list of related technologies are present, it has to be said that not all the data provided seems accurate. For example, the CaC (defined by ESA as the cost to achieve total maturity in a certain technology) for "*20-30kW Electric Propulsion System*" technology is considered at 50 M€ in (ESA, 2016), while in TREx the CaC for the same technology is 19 M€. However, (ESA, 2016) has been considered as database being the same database given to the stakeholders for ESA's prioritization exercise. In Table 11, are shown the results of the prioritization exercise achieved in ESA after two iterations with the ESA Member States and after an internal ranking without ESA Member States support.

This particular process was based on 3 iterations. A first iteration was let internally between ESA representatives only: being them also the people proposing the criteria, this iteration is more accurate and has led to the definition of 10 top priority technologies. In the second and third iteration, ESA Member States representatives where included, looking at people involved in the aerospace industrial sector: during this iteration all the people involved has ranked the entire set of technologies according to the criteria suggested and subjective criteria that are not known. Between these two last iterations, a short workshop has been organized in order to let the people involved speak about their opinions on the future technological priorities. Results are provided in Table 11.

Applying the same method suggested before, the proposed method has a higher similarity with internal ranking results rather than with the two iterations with the ESA Member States. The reason for this is simple: while in the internal ranking the suggested criteria were applied more precisely, even if without an analytical procedure, in the other two cases ESA Member States might have applied different criteria even if the same criteria listed before were suggested. In addition, the proposed method results have a higher similarity with the second iteration results in criteria combination with FoMs in an intermediate range (i.e. not between the combinations with better or worst FoMs). It has to be said that the difference of data in different database can have influenced the stakeholders in considering risks: indeed, different stakeholders might have weighted differently the risk over founding a technology rather than another according to different data used as reference.

Thanks to this exercise, it can be demonstrated that, in order to take into account stakeholders' influence on the case study and their subjective criteria, the formula to choose the final ranking has to be modified with a coefficient able to take into account it. This coefficient will be explained again in the next chapter and is equal to:

$$K = \sum_{i=1}^{N} \frac{s_i}{p_i} \tag{2.8}$$

Multiplying this coefficient to (2.3) or (2.4), it is possible to take into account stakeholders influence and interest in the case study (thanks to a stakeholders' grid approach) and criteria completeness. Again in Table 11 are provided also the results coming from the method proposed, there it can be seen that the method is able to identify about all the 10 top technological priorities identified in the internal iteration. Differences are mainly due to the database incoherence explained before and to a more objective and structured application of the criteria.

Comparing the results achieved in the different combinations of criteria with the second iteration with ESA Member States results is possible to define the influence that the different criteria have on FoMs and results similarity with the real case reference. First, criterion #1, when of high priority in the criteria combination, gives better results when applied in a sense opposite than the proposed one: this criterion gives results with higher similarity with the reference when there are more Space agencies investing in each technology. Criteria #1 and #2 show FoMs in an intermediate range and a medium similarity with the reference, when of high priority in the criteria combination. On the contrary, criterion #5 shows a high similarity with the reference and FoMs in an intermediate range, again when of high priority in the criteria combination. Better is the case of criterion #3 that shows a medium-high similarity with the reference and FoMs in a high range. The worst condition is in all the cases when criterion #4 has high priority in the criteria combination, where the worst values for the FoMs and a low similarity with the reference can be found.

Even if a recreation of the ESA prioritization exercise was not possible, it has to be said that supporting a similar process with the suggestion of a draft technologies ranking based on a rational procedure can simplify the exercise itself reducing interferences from different and subjective strategies. The proposed method can be a logical and quantitative instrument to verify choices of prioritization.

Table 11: ESA prioritization exercise results.

ID	***Technology name***	**Internal order**	**Score 1st iteration**	**Score 2nd iteration**	**TRIS ranking**
1	*Navigation for manned/robotic exploration systems*	3	19	21	3
2	*Storage, sealing systems and Earth return capsule technologies*		20	19	27
3	*Life support technologies*	7	16	18	2
4	*Sample acquisition & handling mechanisms for planetary or lunar application*	4	17	18	9
5	*20-30 kW electric propulsion system*		16	15	4
6	*High speed space communications for exploration*		12	15	25
7	*Radiation Monitoring and Countermeasures*		15	14	6
8	*Ground data sys. techs for monitoring, control, planning/scheduling and simulation of exploration missions*	6	12	14	26
9	*European Stirling Radio-thermal Generator (ESRG)*	9	6	12	7
10	*Advanced mobility: navigation, sensors and operations*		14	11	32
11	*5-kN Bipropellant Engine for ORION-ESM evolution / Ascent stage*	1	9	10	20
12	*Lunar tele-operation technologies*	2	11	10	1
13	*Sample receiving & handling facility: sample handling & contain. sys.*		12	10	29
14	*In-situ material acquisition, handling, processing & investigation*		10	9	21
15	*Data analytics and big data exploitation for exploration missions*		11	9	30
16	*Food production*		12	8	15
17	*3D metal printer*		11	7	23
18	*Sample analysis instr. and techs for planetary or lunar applications*		6	7	33
19	*Refuelling robotics*		4	6	16
20	*In-situ resource extraction and processing*	5	11	6	8
21	*Life support special equipment*		6	5	11
22	*Trash management*		8	5	18
23	*Docking, Entry Descent and Landing (EDL) communications and ranging*		8	5	24
24	*Laser ranging and lunar reference frame generation*		8	5	17
25	*Ka-band dynamically reconfigurable phase-array antenna system*	10	9	4	5
26	*Free-flying multi-purpose CubeSat*		12	3	13
27	*Lightweight crew exercise equipment*		8	2	14
28	*European orbital main engine and TVC for ORION-ESM evolution*		7	2	28
29	*Electronically multi-beam steerable antenna (patch type) for X-band*		6	2	31
30	*Surface EVA suit*	8	6	1	10
31	*Communications relay and spacecraft tracking/localisation*		7	1	12
32	*Fluid pump for coolant loops of crew transportation systems*		2	0	19

2.3.4.3. Other roadmap elements prioritization

Technologies are not the only roadmap elements that have to be prioritized. For example, in case of an Applicability Analysis between BBs and MCs, it will be required at least to move the technologies prioritization on BBs and achieve a prioritization of MCs to define the roadmap. In addition, is simpler to apply stakeholders' criteria on technologies, being they more detailed. On the contrary, BBs, OCs and MCs are particular types of roadmap elements that usually are provided as a support for stakeholders, without being of a high direct interest. For this reason, it is possible to fix criteria for the prioritization of these elements simply based on roadmapping needs.

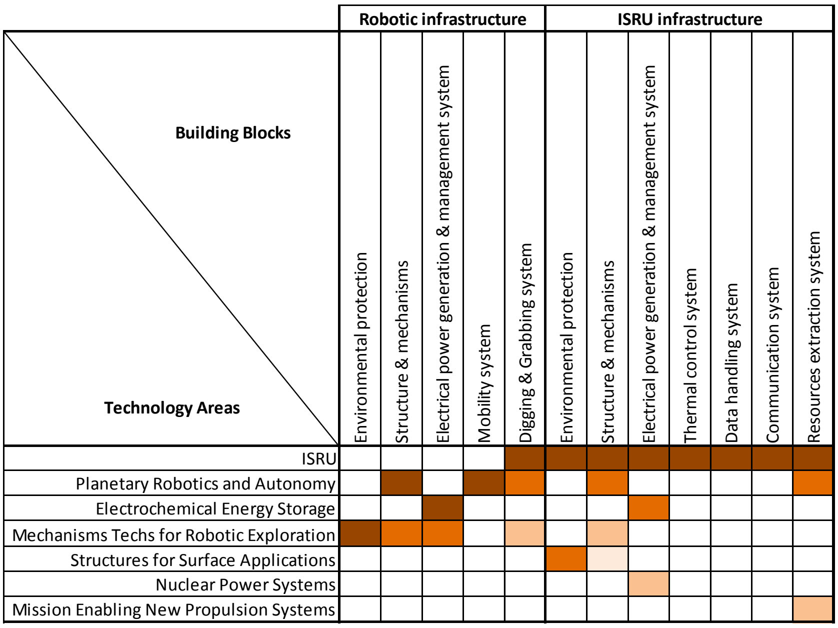
Generally, not all the MCs listed are required or available for the TRL increase and a prioritization of MCs has to be achieved to prune the MCs list to the strictly needed ones. For example, it is important to give different weights to the list of MCs obtained, considering the different level of resources that the MCs require in order to be performed. Indeed, MCs that imply a TRL reached lower than 4 usually require fewer resources, while MCs that imply a TRL reached over 4 show difficulties in their actuation for the involvement of more resources. Another value to be considered is related to the technologies compatibility (i.e. applicability of technologies onto technologies). In case of technologies incompatibilities, the technology with the higher priority has to be considered first. Only after its allocation, the remaining spots can be used for the technology with lower priority (proposing also new MCs to solve incompatibilities and prioritizing them together with the other MCs). Obviously, the MCs have to be ordered in a chronological order to avoid an incorrect choice in the TRL increase path. Another criterion can be related to the percent of technologies that are applied as demo in each MC, in order to consider first the MCs that allow a higher number of applicable combinations at low-medium TRL. Finally, the target environment of every MC is another example, in order to use first the MCs places in an environment nearest to the Earth, considering those MCs the ones that involve lower resources. For example, it is possible to apply in this order to the HERACLES case study the following criteria:

1. Vicinity to Earth of the MC environment;
2. Lower time to wait for MC start;
3. Higher percent of technologies that are applied as demo in each MC (parameter called "demo%" in paragraph 2.3.2).

In particular, it is possible to have the following ordered MCs: Theoretical principles formulation, Analytical proof, Experimental proof, Laboratory components/breadboard validation, Components/breadboard validation in not controlled environment, System/subsystem prototype demonstration in not controlled environment, Components/breadboard validation, System/subsystem prototype demonstration, Complete system flight qualification, Orbital element launch, Follow-on Multi-Purpose Crew Vehicle (MPCV) Missions, LEO Exploitation-Free flyers (e.g. Dragon, Dreamchaser), 2nd Manned MPCV Manned Demonstration Mission, LEO Exploitation - permanent station (ISS, post-ISS Station), 1st MPCV Unmanned Demonstration Mission, Human Assisted Sample Return, Human-lunar surface missions, Human-robotic Partnership Missions, Extended crew duration missions in cis-lunar space, Lunar Polar Sample Return, Luna-Resours-Lander, Human Mars, Mars Sample Return (MSR) preparation / MSR elements, Post ExoMars mission, Enabling long term technology, ExoMars 2018 and ExoMars 2016.

In case of an Applicability Analysis between BBs and MCs and not between technologies and MCs, in order to define the final planning, it is required to translate the technologies prioritization to the BBs: only in this way, it is possible to obtain an at least qualitative prioritization of BBs to be moved on MCs for the final planning. In (Cresto Aleina, 2015c) this situation is analysed and applied to the hypothesis of a change of priority in a OC of (ESA, 2015b), ISRU OC. Being changed the priority of a roadmap element, all the links and data about it will have to be updated in order to propose a planning able enhance this OC in particular.

As it is shown in Figure 34, when a BB is linked to more TAs, it means that the firstly ranked technology has a priority to be developed within that BB with respect to the others. A qualitative prioritization can be performed based on technologies prioritization, simply identifying the BBs that potentially contain the technologies with higher priority and ordering them. In addition, in case of incompatibilities between technologies, the BB has to be doubled in order not to contain incompatible technologies. A similar process can be applied on OCs.



Building Blocks / Technology Areas	Robotic infrastructure					ISRU infrastructure						
	Environmental protection	Structure & mechanisms	Electrical power generation & management system	Mobility system	Digging & Grabbing system	Environmental protection	Structure & mechanisms	Electrical power generation & management system	Thermal control system	Data handling system	Communication system	Resources extraction system
ISRU					🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫
Planetary Robotics and Autonomy		🟫		🟫	🟧		🟧					🟧
Electrochemical Energy Storage			🟫					🟧				
Mechanisms Techs for Robotic Exploration	🟫	🟧	🟧		▒		▒					
Structures for Surface Applications						🟧	░					
Nuclear Power Systems								▒				
Mission Enabling New Propulsion Systems												▒

Figure 34: Applicability TA/BB with prioritization.
White cells means the lower priority level while darker ones means a high priority level.

2.3.5. Planning Definition

To define a TRL increase path is one of the main targets. At the same time, a rule to establish "how much" is required to increase TRL by one is not straightforward. Firstly, TRL update differs among technologies. Second, within the same technology, the increase from say 4 to 5 does not involve the same activities as an increase from 3 to 4. Indeed, the only thing that we are sure about is that by employing a technology in a mission we are likely to increase its TRL. Consequently, the output of our algorithm will consist not only of missions' proposals; this result may in fact be complemented by a series of questions only an expert user is able to answer. Regarding TRL increase, the user may be prompted to express whether the proposed missions qualify for increasing TRL by one. This answer would then update the roadmaps in case new simulations would have to be run. A priori rules can be defined, though. They might have the following form:

"*TRL (new) = TRL (old) + 1 if the technology is applicable to at least n missions*"

A rule that will be explored in this work is to use the connection between the TRL and the environment of a specified MC for a suggestion in the TRL update.

Indeed, an automatic TRL suggestion can be implemented if the tool would be able to see data about the TRL environments (i.e. laboratory environment, relevant environment, operational environment, mission environment…) in the Technology properties. Surely, it is important to add new types of analysis to propose a draft planning to experts for a review such as the available budget analysis, new MCs proposal, TRL increase path definition and schedule definition. Including these analyses to the one analysed or proposed in the previous sections, it is possible to summarize in Figure 35 the main features of the roadmapping methodology proposed.

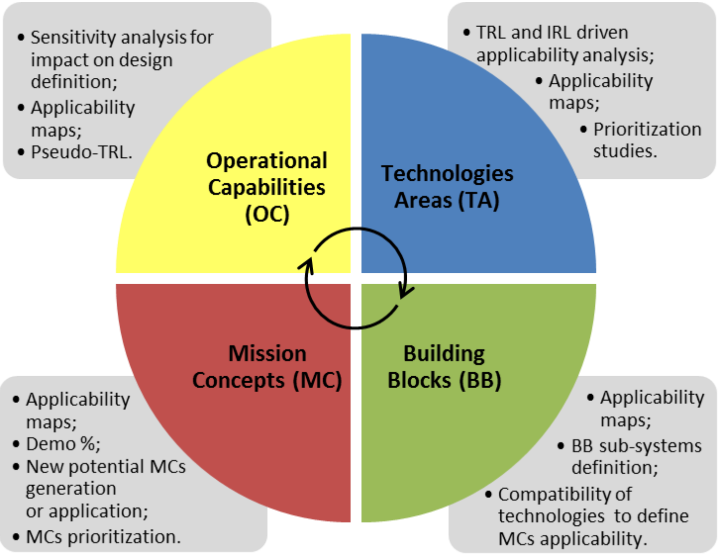


Figure 35: Methodology for roadmap definition and update scheme.

First, in case of a limited available budget, it is easy to understand that not all the technologies will be founded. It can be supposed to maximize the amount of available budget used, distributing it between the different technologies according to their priority. Knowing the CaC of every technology and how this CaC is distributed between the different TRL transit is, therefore, possible to prune the technologies list to the one on which it is possible spending.

Using HERACLES mission as case study, an available budget distribution can be supposed on the basis of the prioritization attempt provided in (Cresto Aleina, 2017e). In particular, trying to reach a TRL of 8 for the 135 technologies a budget of about 900 million € is required is required. Imposing an available budget of 400 million €, only 72 technologies can be reach the desired TRL and two of them will reach an intermediate TRL (i.e. "*Fracture mechanisms of ceramics*" at TRL 7 and "*Low gravity sampling Acquisition & Gathering Mechanisms*" at TRL 5).

While in (Cresto Aleina, 2015b, 2015c) an algorithm for *new MCs proposal* on the basis of an Applicability Analysis between BBs and MCs is proposed, easier is the case of proposing a similar algorithm on the basis of an Applicability Analysis between technologies and MCs. The first algorithm creates new missions or applies relevant BBs to existing missions starting from the definition of MCs as union of BBs, i.e. $M_i = \bigcup_k BB_k$. On the contrary, when every applicability map is focused on technologies, it is simpler to define new missions. For example in (Cresto Aleina, 2017b) it is proposed a different approach. Through a high level ConOps definition, it is possible to define feasible missions and the relative Modes of Operation starting from Mission Statement. Combining missions and Modes of Operations is then possible to define MCs including demo missions. In addition, having defined every Modes of Operations with the technologies that can be active in it, it is possible to combine missions and technologies. Finally, an analysis based on technologies incompatibilities (i.e. applicability of technologies onto technologies) is required to propose missions with compatible technologies.

Particularly, during the *TRL increase path* evaluation, the following additional constraints have to be considered:

- The actual TRL: the MCs that refers to missions that are not required for the TRL increase have to be neglected;
- The presence of testing environments in the Technology properties: the missing environments can be neglected in the TRL increase evaluation;
- The presence of technologies incompatibilities (i.e. applicability of technologies onto technologies).

At this point, it is possible to propose a TRL increase path combining TRL transits and MCs able to perform it. This is possible assuming a step by step approach in the TRL increase (i.e. one mission performed is equal to one level added in the TRL) and using the data listed above. Having data about time in the MCs properties is possible, finally, to propose a *schedule* simply ordering the selected MCs according to technologies TRL. It has to be said that a statistical analysis can be a support.

Using again HERACLES mission as case study, a planning example can be provided in (Cresto Aleina, 2017f), where the reference mission has been analysed, simplified and a TRL increase path has been proposed. Simplifications are there imposed to focus on critical TAs or situations in the planning definition. For example, important constraints are the sub-system to consider selecting only sizing functions, the target environment, the final TRL to reach and the launch year (Table 12) (Hufenbach, 2015). In addition, two BBs will be considered as starting point and an OC will be analysed at the end to verify the results.

Table 12: HERACLES mission data.

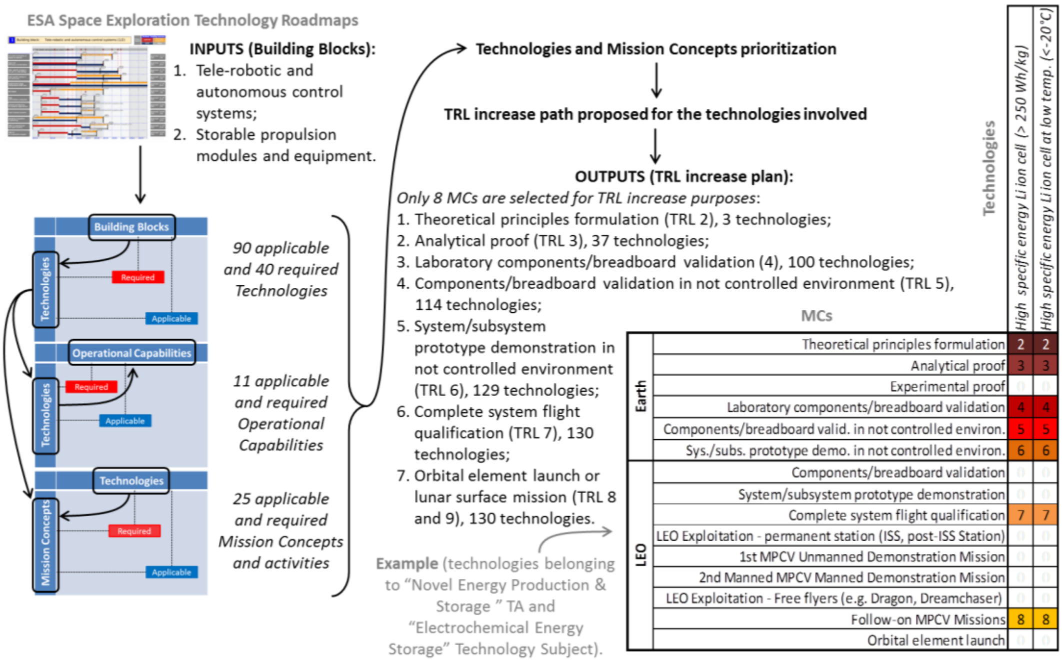
Target environment	Moon
TRL to reach	8
Launch year	2024
BBs of interest	*Tele-Robotic And Autonomous Control Systems /* *Storable Propulsion Modules And Equipment*
OCs of interest	*Robotic/Tele-Robotic Surface Operations*
Analysed sub-systems functions	Structure and mechanism, electric power generation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

Figure 36 shows the methodology applied. Thanks to this methodology, it is possible to define a list of 130 technologies related to the starting 2 BBs, covering 9 TAs and divided into 90 applicable technologies and 40 required ones. These technologies are related to 11 OCs and 25 MCs.

Considering technologies incompatibilities, only 8 types of MCs are applicable for TRL increase purposes on Earth, in LEO and on the Moon, but not all these missions are required and, applying MCs prioritization and technologies prioritization, the following ones can be proposed for the final TRL increase path:

1. *Theoretical Principles Formulation* activity, used to reach TRL 2 in 3 technologies;
2. *Analytical Proof* activity, used to reach TRL 3 in 37 technologies;
3. *Laboratory Components/Breadboard Validation* activity, used to reach TRL 4 in 100 technologies;
4. *Components/Breadboard Validation In Not Controlled Environment* activity that is used to reach TRL 5 in 114 technologies;
5. *System/sub-system Prototype Demonstration In Not Controlled Environment* activity that is used to reach TRL 6 in 129 technologies;
6. *Complete System Flight Qualification* activity, used to reach TRL 7 in 130 technologies, proposed ad-hoc and with a final “demo%” of 100%;

7. *Luna-Resours-Lander* programme, used to reach TRL 8 in 130 technologies, starting from a “demo%” of 74% and ending with the same value after the TRL 7 demonstrative mission.



INPUTS (Building Blocks):

1. Tele-robotic and autonomous control systems;
2. Storable propulsion modules and equipment.

OUTPUTS (TRL increase plan):

Only 8 MCs are selected for TRL increase purposes:

1. Theoretical principles formulation (TRL 2), 3 technologies;
2. Analytical proof (TRL 3), 37 technologies;
3. Laboratory components/breadboard validation (4), 100 technologies;
4. Components/breadboard validation in not controlled environment (TRL 5), 114 technologies;
5. System/subsystem prototype demonstration in not controlled environment (TRL 6), 129 technologies;
6. Complete system flight qualification (TRL 7), 130 technologies;
7. Orbital element launch or lunar surface mission (TRL 8 and 9), 130 technologies.

Example (technologies belonging to “Novel Energy Production & Storage ” TA and “Electrochemical Energy Storage” Technology Subject).

		High specific energy Li ion cell (> 250 Wh/kg)	*High specific energy Li ion cell at low temp. (<-20°C)*
Earth	Theoretical principles formulation	2	2
	Analytical proof	3	3
	Experimental proof	0	0
	Laboratory components/breadboard validation	4	4
	Components/breadboard valid. in not controlled environ.	5	5
	Sys./subs. prototype demo. in not controlled environ.	6	6
LEO	Components/breadboard validation	0	0
	System/subsystem prototype demonstration	0	0
	Complete system flight qualification	7	7
	LEO Exploitation - permanent station (ISS, post-ISS Station)	0	0
	1st MPCV Unmanned Demonstration Mission	0	0
	2nd Manned MPCV Manned Demonstration Mission	0	0
	LEO Exploitation - Free flyers (e.g. Dragon, Dreamchaser)	0	0
	Follow-on MPCV Missions	8	8
	Orbital element launch	0	0

Figure 36: Scheme of the case study application.

It can be seen how the proposed methodology is able to choose a final mission (i.e. the proposed lunar surface MC) similar to the reference one. Indeed, in (ESA, 2015b) this MCs is called “*Luna-Resours-Lander*”, and indicates ESA contribution to a Russian-led mission called “*Luna 27*”, aimed at investigating the lunar surface and subsurface in the South polar region and at validating advanced lunar exploration. It has to be said that currently HERACLES mission is included in TREx, but for the purposes of this exercise it has been hidden referring only to (ESA, 2015b) to check TRIS behaviours. Finally, looking at the reference OC, its pseudo-TRL increases from 3.13 to 8, supposing to be able to fulfil the entire proposed roadmap. This high increase is related to the high number of technologies involved through the two BBs and to the fact that all these technologies where related to the OCs under analysis.

2.3.6. Results Evaluation

At this point, a nominal planning can be proposed and some studies performed to verify it and propose corrections to stakeholders. In particular, it is important to verify out-of-nominal situations (e.g. technical, economic or political risks) or to evaluate the impact on the results of stakeholders inputs (e.g. the TRL to reach).

To evaluate risks it is possible to define the AD2 of each technology. Even if through (ESA, 2015a) it is possible to have a TRL value for every technology, this is not true for the AD2 that has to be estimated. A relation between TRL and AD2 is proposed starting from literature (Cresto Aleina, 2017e). A difference from (Bilbro, 2006) is in the possibility to apply technologies in a reference target environment different from the one originally intended for the each technology. In particular, it is possible to have a technology originally in a more complex target environment, a technology originally in a simpler target environment or a technology originally in the same target environment. Analysing AD2 and TRL definitions and supporting this analysis with (Bilbro, 2006), it is possible to propose a method to estimate AD2 (Figure 37 and Table 13).

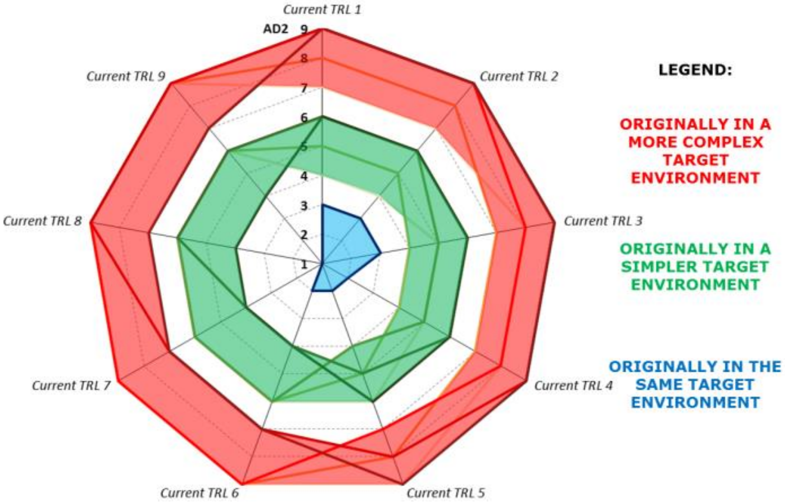


Figure 37: AD2 and TRL relationship scheme.

Table 13: AD2 and TRL relationship.

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

Again, in (Bilbro, 2006), a direct link between AD2 and risk is suggested. Reaching a risk estimation is important, considering that (INCOSE, 2015) defines it as the product between the probability of failure and the consequences of this failure. The risk studied in this matrix is related to safety, technical or cost and schedule issues (Alcorn, 2009). A risk matrix has been proposed (Figure 38) considering some simple rules:

- Consequences have a higher weight than likelihood of failure: a multiplier of 3 is introduced to proportionally increase the relative weights, choosing it as the minimum one at which the risk matrix and the AD2 levels on it are at an asymptote;
- Both first levels have a weight of 1 to consider this situation negligible;
- Likelihood of failure last level is considered ways more severe than the other levels, using a weight of 6.

If the risk is the product between likelihood and consequences (INCOSE, 2015), the reciprocal weights have the same relationship. Therefore, the low, medium and high-risk areas on the diagram are finally fixed multiplying for each cell of the matrix the consequence and likelihood weights and fixing the two boundaries at the 30° percentile and at the 70° percentile of the resulting weights distribution (Figure 39). Finally, in (Bilbro, 2006) every AD2 level is directly related to an interval of risk percent: performing the same percentile study, it is then possible to find nine different areas one for each AD2 level. The exact risk cell in the matrix for every AD2 level is found remembering that a higher consequence level is considered more severe than a higher likelihood level.

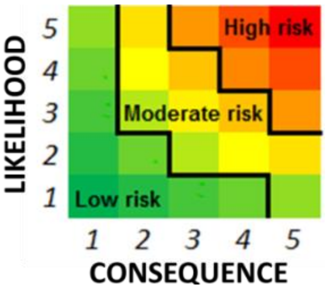
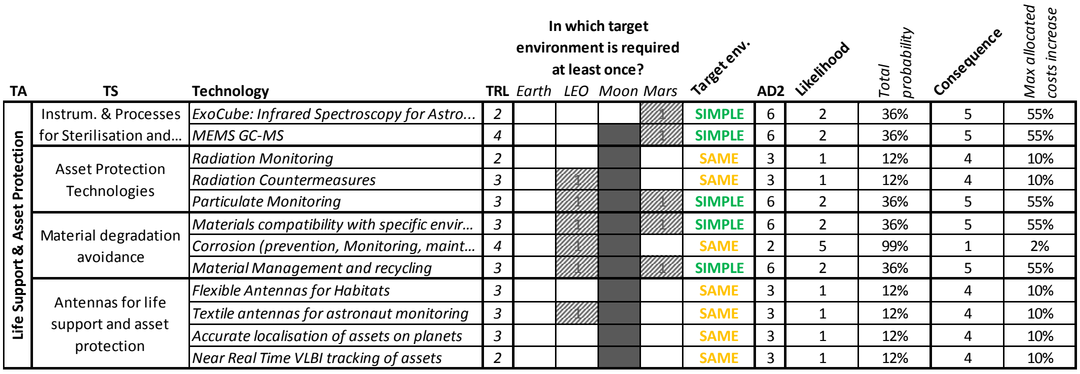


Figure 38: Proposed risk matrix.

Applying this process to the HERACLES case study is possible to estimate AD2 level, likelihood of failure and maximum allocated costs increase for the involved technologies. This is possible assuming as likelihood of failure for the five risk matrix levels respectively 12%, 36%, 63%, 89% and 99% (total probabilities between safety, technical, cost and schedule likelihood of failure) and assuming a maximum allocated costs increase percent from (Alcorn, 2009). This is also possible remembering the Applicability Analysis between MCs and technologies, from which it is possible to know in which target environment each technology is currently under study. Figure 39 shows an example of result for the first TA of (ESA, 2015b). Thanks to this analysis, it is possible to have a first draft estimate of risks and consequences including a draft estimate of the maximum allocated costs increase knowing the CaC of each technology.



				In which target environment is required at least once?									
TA	TS	Technology	TRL	Earth	LEO	Moon	Mars	Target env.	AD2	Likelihood	Total probability	Consequence	Max allocated costs increase
Life Support & Asset Protection	Instrum. & Processes for Sterilisation and…	ExoCube: Infrared Spectroscopy for Astro…	2				1	SIMPLE	6	2	36%	5	55%
		MEMS GC-MS	4			■	1	SIMPLE	6	2	36%	5	55%
	Asset Protection Technologies	Radiation Monitoring	2			■		SAME	3	1	12%	4	10%
		Radiation Countermeasures	3		1	■		SAME	3	1	12%	4	10%
		Particulate Monitoring	3		1	■	1	SIMPLE	6	2	36%	5	55%
	Material degradation avoidance	Materials compatibility with specific envir…	3		1	■	1	SIMPLE	6	2	36%	5	55%
		Corrosion (prevention, Monitoring, maint…	4		1	■		SAME	2	5	99%	1	2%
		Material Management and recycling	3		1	■	1	SIMPLE	6	2	36%	5	55%
	Antennas for life support and asset protection	Flexible Antennas for Habitats	3			■		SAME	3	1	12%	4	10%
		Textile antennas for astronaut monitoring	3		1	■		SAME	3	1	12%	4	10%
		Accurate localisation of assets on planets	3			■		SAME	3	1	12%	4	10%
		Near Real Time VLBI tracking of assets	2			■		SAME	3	1	12%	4	10%

Figure 39: AD2 analysis results.

Using the prioritization of technologies achieved through criterion #4 of the previous HERACLES example, it can be analysed how an additional TRL to reach value affects the available budget distribution, fixing the available budget and looking at the best way to spend it (Table 14). It can be seen that applying a lower TRL to reach means including more technologies, while applying a high TRL to reach means performing more TRL steps for fewer technologies. Costs are there evaluated starting from the CaC of each technology and the results obtained in the AD2 analysis.

Table 14: TRL to reach analysis.
Purple line refers to the value of reference for this case study values, red values are used to highlight the maximum values and green values are the minimum one.

TRL to reach	N of TRL variations	Techs involved	Techs at final TRL	Techs already at TRL	Cost (€)	Cost (%)
9	480	**3**	73	**0**	€ 399'870’725	100%
8	**407**	**3**	**72**	**1**	**€ 399'870’725**	**100%**
7	354	**3**	77	1	€ 399'918’634	100%
6	279	**3**	79	2	**€ 399'957’442**	**100%**
5	242	**3**	100	17	€ 399'798’125	100%
4	146	**3**	**104**	31	€ 206'103’913	52%
3	42	**3**	39	96	€ 43'133’591	11%
2	3	**3**	**3**	**132**	**€ 600.000**	**0%**

Additional analysis will have to be proposed. Indeed, remembering the definition of a SoS is easy to understand that social and political issues or requests can have an influence on the roadmap describing its development. All these factors can create delays and over-costs. It is important to define and categorize the possible factors that can have an influence on the nominal roadmap and this to evaluate this roadmap feasibility. Determining delays and over-costs, means defining possible out-of-nominal situations.

2.4. Roadmap Visualization and Update

As previously explained, in a roadmap a significant role is played by its graphical layout and for a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme EIRMA approach has to be proposed. The proposal of new visualization type depends on stakeholders' needs, but, being the purpose of the roadmap defined to support design activities and decision-making processes visualizations able to show links between elements, current strategies and budget and time distributions will have to be preferred.

In addition, it is required to give the possibility to a stakeholder to focus on elements different from technologies. Indeed, from previous analysis it is clear that the focus on the methodology that can be proposed is on the technologies, both for data availability and analysis simplicity. While technical stakeholders might ask for a roadmap based on technologies, non-technical ones might ask for roadmaps based on different elements able to provide a wider scenario. This is the case of the "reverse roadmaps" (ESA, 2015b), i.e. roadmaps that focus on elements that are different from technologies.

Once defined the roadmap, an important phase is the data update and review. Indeed, with time, pseudo-TRLs advance, mission scenarios progress and technologies TRLs increase. In addition, the properties of the different roadmap elements 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 aimed at optimizing the final roadmap and at keeping it updated.

2.5. Highlights

- ✓ Using examples in the European space exploration scenario, studies will be proposed to size every TRIS phase and their results according to the SoS architecture features;
- ✓ The typical System Design Process is proposed in the Preliminary Activities to define roadmap scope and boundaries in order to have a clear view of the current scenario in terms of market possibilities, current state of the art and design and mission constraints starting from the market and stakeholder' needs analysis;
- ✓ Systems Engineering, Decision Analysis and Program Management tools and theories are applicable to the roadmap definition process and a methodology based on them has been studied to support the roadmapping approach;
- ✓ In the context of an ongoing large-scale collaborative programme, EIRMA has to be proposed for visualization purposes in order to adapt the roadmap to stakeholders' needs and to support update and decision-making processes. According to EIRMA approach a roadmap has to show links between elements, current strategies and budget and time distributions approach.
- ✓ Two examples of complete application will be proposed: Hypersonic Space Transportation (to verify TRIS application) and Re-Entry Systems and Reusable Space Tugs in Earth Vicinity (to check for results consistency).

Chapter 3

Evolution of Roadmapping Methodology: Technology RoadmappIng Strategy (TRIS)

As main result of all the studies performed, a final methodology can be proposed able to derive strategic planning in the field of a mission-oriented roadmap describing a SoS in the context of an ongoing large-scale collaborative programme: TRIS. In addition, this methodology is based on Systems Engineering, Program Management and Decision Analysis theories and tools and is a comprehensive methodology to derive and update technology roadmaps (Figure 40).

In particular, TRIS is a rational, data-based and normative roadmapping methodology able to define and manage mission-oriented roadmaps in the context of an ongoing large-scale collaborative programme. TRIS first step is the "*Roadmap elements definition and characterization*". The main purpose of this step is to define and categorize all the elements related to the case study, starting with the stakeholders' needs analysis and leading to a complex system. In particular, this step is based on a high-level design process that allows generating every roadmap element as modular and already organized in the SoS. In this step of the methodology, Systems Engineering tools and theories are exploited. Then it proceeds with the "*Applicability Analysis*", which is one of the fundamental tools used of the methodology to link elements, describing the strict correlation between them. The Applicability Analysis depends on the Functional Analysis (to define if two elements are related and given as an input from the previous phase) and on Market and Stakeholders' Analysis (to define the importance of the link). "*Sensitivity Analysis*" follows to weight the reciprocal link importance and optimize the results obtained based on market and stakeholders' needs. Then the "*Prioritization Studies*" phase is required and exploits Decision Analysis tools to rank the elements, in order to suggest and weight preferable paths to be followed in the roadmap definition. Indeed, the outputs from this analysis are crucial for the "*Planning Definition*", where missions and technologies are combined to reach the maturity required by the stakeholders. Finally, with "*Results Evaluation*" the obtained roadmap is verified suggesting delays and over-costs based on the proposed TRL increase path.

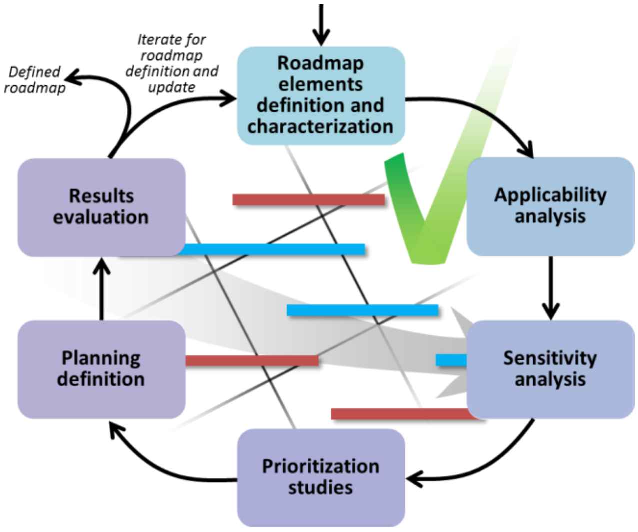


Figure 40: TRIS Main phases.

Finally, once this process is completed, all data need to be updated and (at least periodically) reviewed. This implies that the elements lists have to be integrated with innovative or future solutions, the elements features can change and their maturity increases. This is an iterative and recursive process aimed at outlining an optimized Technology Maturation Plans and at providing it to the final users.

Main benefit of this methodology is a complete traceability of stakeholders needs and other requirements till from the beginning of the planning phase (i.e. the roadmap definition and the feasibility studies), thanks to a System Engineering approach. In addition, thanks to Decision Analysis tools and theories, it is possible to rationalize the process, reducing subjective logics and criteria. In addition, having a sequential method as a support for the roadmap definition is also a way to reduce roadmap time to users. In this way, the final roadmap is an objective planning to be proposed to users and experts for validation and able to reduce roadmapping activities duration, even if only a draft result of TRIS.

3.1. TRIS Main Features

The logical process here proposed would be exploited in and be beneficial for very different domains dealing with SoSs, in the specific case of a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme. It has to be said that Systems Engineering theories and tools application is both a strength and a limitation. On one side, the application of Systems Engineering theories ensures a certain level of modularity in the roadmap elements, useful to make the derivation and update process applicable to different kind of strategic roadmap elements (e.g. technology-pull, mission-pull…) or to different type of approaches. On the other side, the modularity itself is an important requirement that has to be matched.

Considering Systems Engineering tools, Functional Analysis is surely a significant support in the *Roadmap elements definition and characterization* and in the *Applicability Analysis*. In particular, while Functional Tree and Products Tree are there exploited to derive the roadmap elements (i.e. BBs, TAs and OCs, further defined through trade-spaces), Function/Product Matrixes are exploited to derive the main links between different elements.

Another feature that constrains the proposed method is the mission-oriented approach. Even if a similar approach simplifies the comparison between the planning data and the System Design process features, a limit in this approach is in the inability to find new types of technologies unless experts are involved. An assumption made to overcome this is limiting the technologies list to a single sizing feature: it is not easy to found the necessity of new features, unless stakeholders will not require them.

Another important TRIS feature is in the role of Decision Analysis, that is a crucial support for decision makers and can lead to the optimization of the proposed final solution (i.e. the final roadmap TRL increase path). In every step of

TRIS Decision Analysis is applied to drive decisions taking into account the high number of stakeholders and the multiple (and sometimes conflicting) objectives. In particular, Decision Analysis is important in the *Applicability Analysis* (i.e. in supporting the choice of possible correlations between couples of elements), the *Sensitivity Analysis* (i.e. in the quantification of the previous phase correlations) and in the *Prioritization Studies* (i.e. in relating stakeholders strategies with the definition of ordered list of elements).

Finally, Program Management theories are there an important support and this is particularly true in the *Results Evaluation* phase. Indeed, in this phase social, economic and political influences play the main role in analysing the nominal schedule in order to propose out of nominal situations, over-costs and delays.

3.2. TRIS: Preliminary Activities

In defining a roadmap, every process starts with the definition of roadmap scope and boundaries in order to guarantee the satisfaction of the stakeholders' essential conditions. As previously explained, in this phase the typical System Design Process is proposed, defining scope and boundaries means the definition of a Research Study Objective, Stakeholders' Analysis and constraints definition. The process starts with a stakeholder analysis to define the basic constraints for the final roadmap, such as final TRL, budget, schedule and milestones. Thanks to and in combination with this analysis, it is then possible to start a high-level mission analysis defining through the Research Study Objective analysis all design solutions able to meet stakeholders' needs. Market analysis has always to be taken into consideration to constraint the analysis in order to obtain a result able to be competitive and realistic. In particular, it is important to define the following data:

- Programmatic requirements such as the total amount of resources available, time frame available for the planning, final TRL to be reached and strategic target environments;
- Strategic criteria that might drive decisions according to stakeholders;
- Stakeholders impact and influence (through a strategy grid);
- Design boundaries in terms of constraints that might be applied as constraints on the roadmap elements.

After preliminary activities, the main requirements needed to be compliant with stakeholders' needs, regulations and other imposed constraints are an important input for the identification of four elements. It has to be remembered that stakeholders have to be categorized according to their main areas of interest of the involved stakeholders and that each areas can be mapped on a stakeholders' grid according to Figure 14. The main areas of interest of the involved stakeholders are:

1. *Final mission needs*, considering in this categories all the situation and the stakeholders related to the mission of reference, requiring the solution that guarantee only the mission success;
2. *Political needs*, considering all the stakeholders and the situations that can influence the results in term of political inference (e.g. to promote technologies with faster or unique results);
3. *General public needs*, considering all the stakeholders that need the final result to promote missions or technologies with an high impact, for example, on news;
4. *Economic needs*, considering all the needs related to resources availability and economic issues;
5. *Scientific needs*, considering in this group all the requests related to the scientific payload operations and results;
6. *Technological needs*, considering in this category the needs related to technological enhancement.

3.3. TRIS: Roadmap Development

TRIS is a methodology for technology roadmaps managing and has been proposed and applied, such as in (Cresto Aleina, 2016c, 2017e, 2017d), with the aim of reducing the roadmapping efforts proposing an optimized result at the early phases to the stakeholders, reducing time-to-market. In this way, it is possible to decrease temporally the stakeholders' involvement and to reduce the results subjectivity. TRIS is based on all the studies performed on space exploration roadmapping efforts described in the previous chapter, in which a certain number of tools, analysis and parameters have been derived (Figure 35). To ease TRIS application in these case studies, it has been implemented in an ad-hoc studied toolchain involving MS Office Excel® and Matlab® (Figure 41).

During the process is important to relate this toolchain with databases containing experts' data or with data estimations. Indeed, it is important to at least estimate the available data about past, on-going and foreseen products and events in a certain scenario with the aim of supporting the roadmap generation and update process. In particular, a generic roadmapping database should support roadmapping activities in collecting data, providing statistical trends and suggesting current strategies and roadmaps if present.

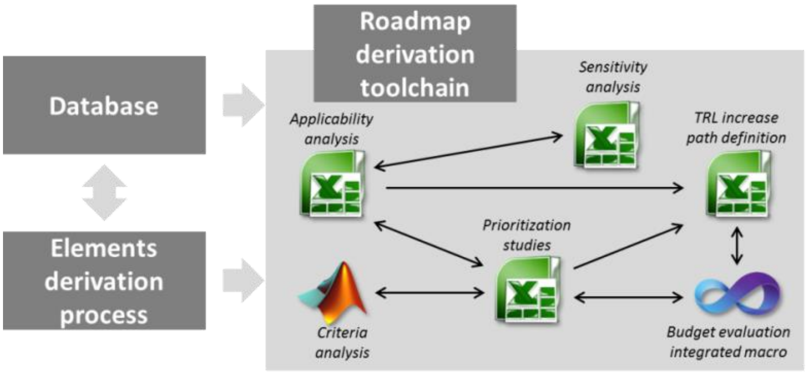


Figure 41: Technology roadmap definition and update methodology toolchain.

3.3.1. Roadmap Elements Definition and Characterization Process

The very first step of TRIS is the "*Roadmap elements definition and characterization*", defining and categorizing all the elements related to the case study. In this step of the methodology Systems Engineering tools and theories are exploited: after the preliminary activities, analysing the requirements it is possible, through a typical System Design Process applied a high level of detail (Viola, 2012; Cresto Aleina, 2016d), to define a list of action that products have to perform to be compliant with the requirements itself (Figure 4). Exploiting a similar process allows the definition of every roadmap element as modular and already organized with all other elements highlighting reciprocal links inside the SoS under analysis (Figure 42, Figure 43, Figure 47 and Figure 48).

Functional Analysis deals with functionalities and products and it is particularly useful to list, categorize and analyse OCs, BBs and technologies. In addition, functions and Products Trees can define sub-categories of elements that will have to be included, but trade-studies are required better define elements list in accordance with stakeholders' needs. In particular, it is possible to exploit Functional and Products Trees to define categories of OCs, BBs and technologies (i.e. defining TAs and Technology Subjects as categories of technologies) and to exploit an approach similar to a trade space analysis to define the final lists

(Figure 43). A trade space is a multi-variant space, mapping possible design solutions composed by them (McNamee, 2001).

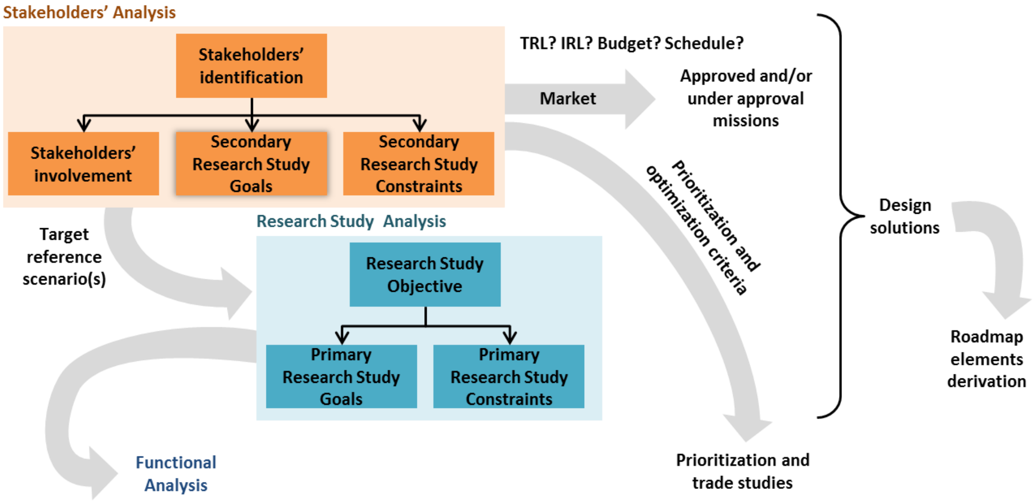


Figure 42: Preliminary activities process overview.
This first phase produces as output the input for BB, TA, OC and MC derivation.

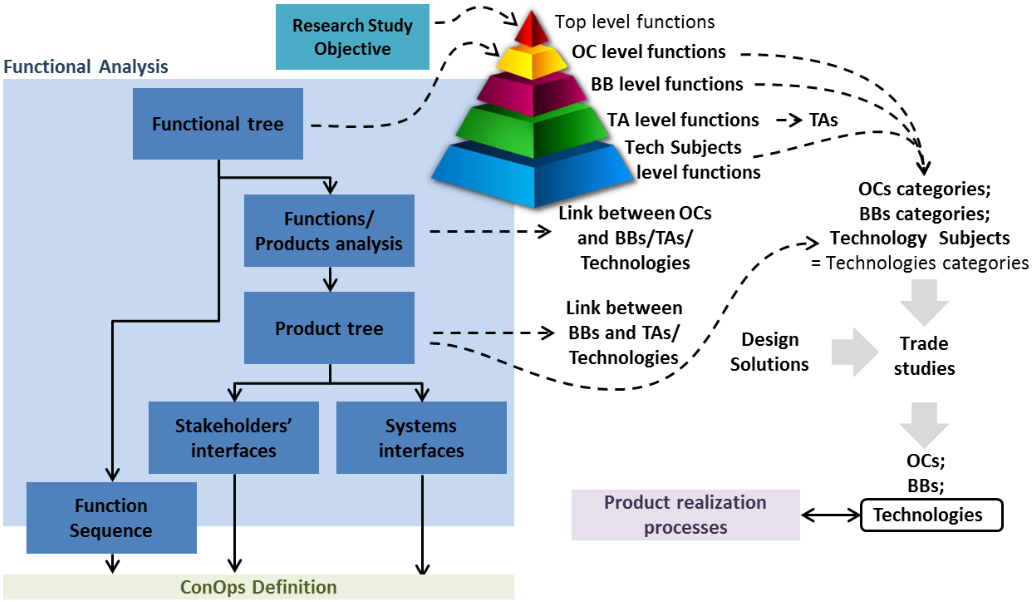


Figure 43: Functional Analysis use in methodology for BB, TA, OC and MC derivation and main database settings.

Being the OCs defined as a performance requirement, it is required to combine the Functional Tree results (i.e. OCs categories) with the performance that constraints or enhances the case study. For each OCs category, a trade space can be defined, using as "variables" different mission features containing a certain number of possibilities for each feature and a single group of performance types, collecting all the strategic trends required by stakeholders for each performance. On the contrary, for each BBs category a trade space can be defined, using different groups of design choices made by the stakeholders, containing different possibilities for each design choice. OCs and BBs will be defined combining a possibility for each trade space variable. It has to be remembered that important data have to be found for each element such as risky situations or competitiveness in implementing a certain "variable" in each BBs or OCs TRL. In addition, it can be useful to estimate SRL for each BB. To propose this the relationship between SRL definition and US DoD life-cycle phases can be exploited: when this data are known for a BB SRL can be estimated directly.

Also to derive the technologies, additional analyses have to be proposed. Firstly, it is required to define statistically the features that usually describe a Technology Subject and to define which one is the sizing feature. For example, a Technology Subject can be "*Trace Gas Analyser*" inside the "*Environmental Control and Life Support system*" TA, usually described by "Mass" (kg), "Volume" (m^3) and "Power Consumption" (kW). Being its TA an important system when present, a feature that has to be guaranteed representing the driving requirement can be the "Power Consumption". Technologies for this subject can be obtained dividing the range of Power Consumption into three levels (i.e. low, medium, high): Trace Gas Analyser with *low* power consumption, Trace Gas Analyser with *medium* power consumption and Trace Gas Analyser with *high* power consumption. Low, medium and high ranges can be obtained statistically from the existing technologies and stakeholders expectations.

The definition of the three sizing feature levels is supported by a statistical analysis based on decision-making processes and based on database availability. Being a database available, the sizing performance can be subdivided into categories analysing its distribution between the current technologies categorize into the same Technology Subject: this feature can adapt the roadmap to future technological and market advancement. It has to be remembered that important data have to be found for each element such as TRL, CaC and time to reach maturity for the technologies. A useful link that might help in defining TRL and time to reach maturity is (Copeland, 2015) that shows how these data are related to US DoD life-cycle phases. Thanks to this, it is possible also to estimate SRL when is not possible directly: identifying the technology at the wort condition (i.e. with lower TRL), it is possible to derive the US DoD life-cycle phase for it and derive the SRL for the worst condition.

Finally, ConOps definition at a high level is the basis on which propose MCs and relate them to the other groups of elements (Figure 45 and Figure 47). Indeed, taking into account the advancement and funding (Cresto Aleina, 2016b), MCs can be subdivided into three different categories (i.e. approved MCs, under approval MCs, potential MCs) and derived according to them. While approved MCs are not significant for a roadmap proposal not being modifiable and are relevant only to estimate the current state of the art, under approval MCs can support future planning. In both cases, these MCs are related to the MCs currently available from the stakeholders involved: knowing them is possible to ask for their current activities and list them. Potential MCs have to be estimated and there the ConOps definition might help. Indeed, it is possible to derive the common Mission Phases remembering preliminary activities outputs: identifying the different Mission Phases and knowing the starting and ending environments is possible to compose them to propose potential MCs. Indeed, operational MCs are the Mission Phases combinations able to move a system between two strategic target environments. On the contrary, demonstrative MCs includes both the previous ones and partial operational MC (i.e. focusing the demo proposal only on the phases involved in the demo and not in initial, intermediate or final transfers).

Also in this case, it has to be remembered that important data have to be found for each MC such as Modes of Operations active in the different Mission Phases, actual demo%, MC timing (i.e. launch date, starting and ending time), financial resources to be added only for a MCs implementation without considering the technologies involved (or at least a weight able to order the MCs according to their costs) and usual TRL allowed in that specific MC for the considered technologies. Thanks to the Modes of Operations definition, it is outlined at least which Technology Subjects active or not in each mode: this is useful in the next phase.

It has to be remembered that additional technologies related to the Product Realization Processes shall be included, i.e. all the processes aimed at creating, verifying and validating the products according to the defined requirements. The main reason for this is in the need of verify, validate and product the previously identified technologies and, therefore, also all the tools and facilities related to it (e.g. considering the software required to simulate in the loop every previously obtained technology during Product Validation Processes). Indeed, it is useless to have a TRL increase path for a technology, when there is not the possibility to validate, verify or produce it because all the technologies related to its validation, verification and production are not at an adequate TRL. A process has been supposed on the basis of (NASA, 2017), even if there is not applied for simplicity (Figure 48) considering the need of a strong expert involvement.

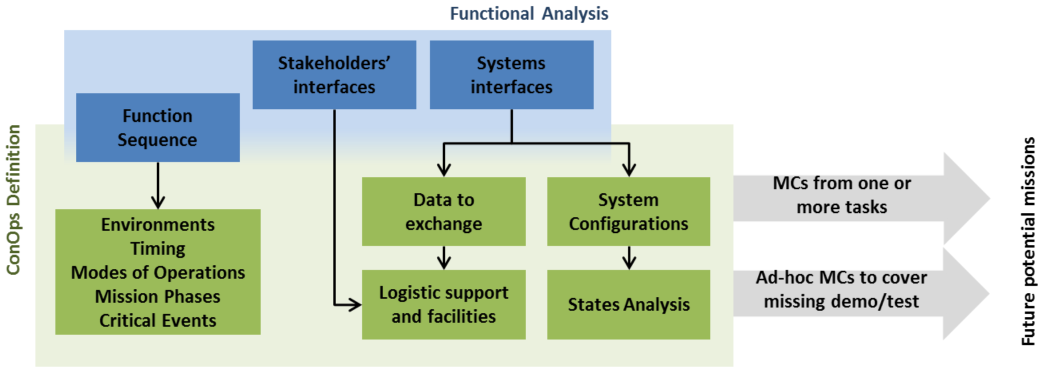


Figure 44: ConOps use in the methodology for BB, TA, OC and MC derivation and main database settings.

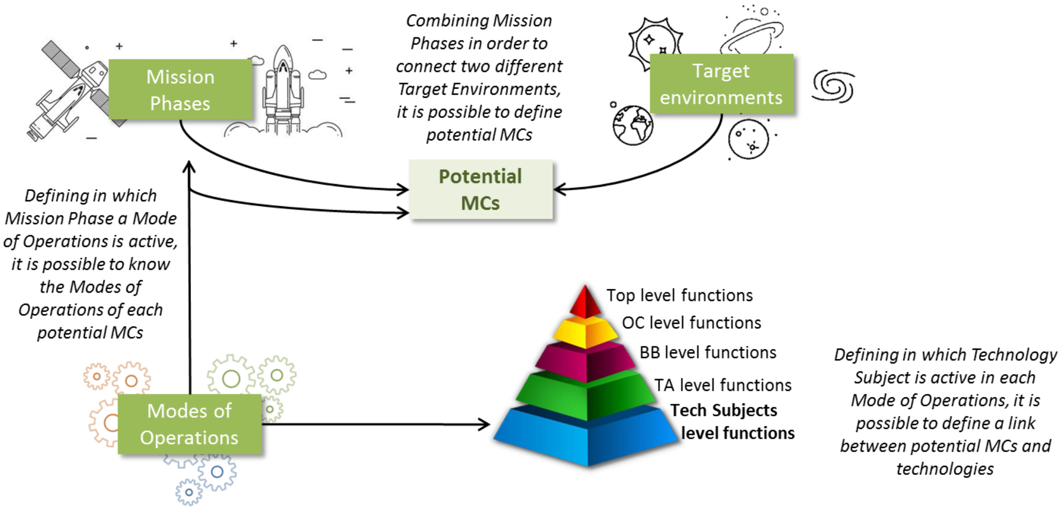


Figure 45: MCs definition process and possible link with Technology Subjects.

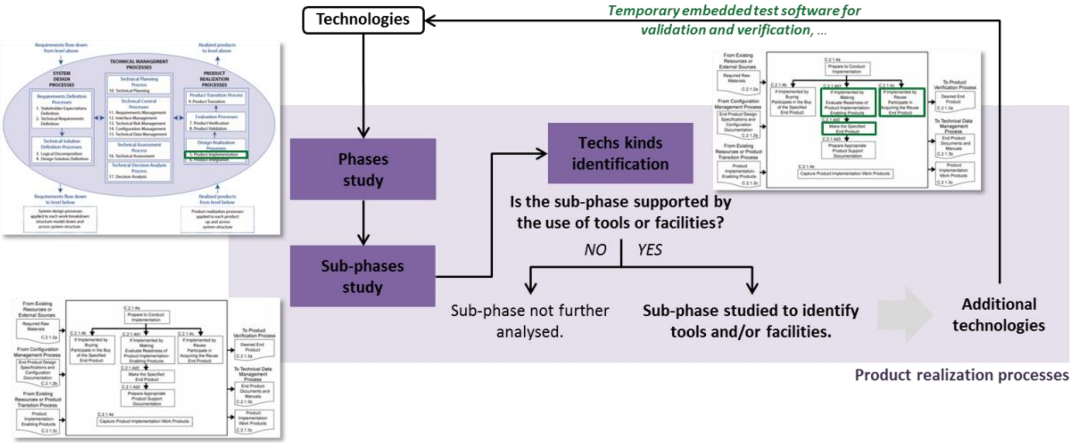


Figure 46: Product realization processes contribute to the methodology for BB, TA, OC and MC derivation and main database settings.

An example based on (NASA, 2017) is present. In the examples provided this part is not reported for simplicity: expert opinion is required to give details to this phase.

3.3.2. Applicability Analysis

Every elements link derived in the previous phase is the basis on which derive applicability maps in the "*Applicability Analysis*". This phase is one of the fundamental tools to describe the strict correlation between the elements involved. Indeed, this analysis is proposed to detect possible correlations between couples of elements coming from the same or from different groups and to highlights the importance of these connections (Cresto Aleina, 2016c). In this phase, Decision Analysis gains importance. Indeed, it is true that it still depends on the Functional Analysis (especially from Functions/Products Matrix), on Market and Stakeholders' Analysis (to verify the importance of the link) and on the ConOps definition (from the link between Technology Subject and MCs through the Modes of Operations). In addition to this, Decision Analysis is also important in the definition and sizing of the elements correlation. For example, a decision tree approach can be proposed to define correlations between different groups of elements or to define technologies compatibilities (Cresto Aleina, 2016b).

Four types of applicability maps are here considered: applicability of TAs/technologies onto OCs, applicability of TAs/technologies onto BBs, applicability of technologies onto technologies and applicability of MCs onto TAs/technologies (Figure 47). In the applicability analyses between different groups of elements, the relationship between two elements is described by three labels: "required" (i.e. highly affecting relationship) and "applicable" (i.e. relevant but not strictly needed relationship) and “not applicable” (i.e. not needed or not possible relationship). Required, applicable and not applicable are considered as “labels” and will be weighted through sensitivity analyses in such a way to describe clearly the stakeholders’ expectations (see “*Sensitivity Analysis*” phase). A first nominal set of weights is 1, 2 and 0 respectively.

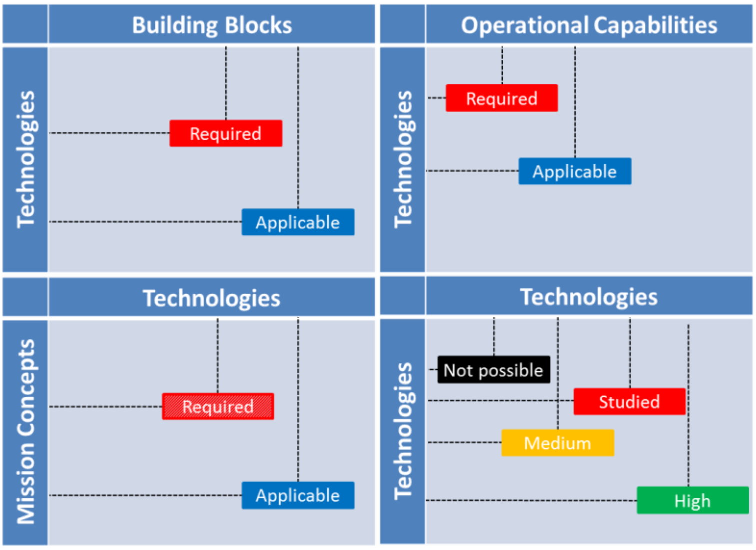


Figure 47: Applicability analyses.

Another important feature of this “labels” is that they have to be related to the stakeholders (i.e. define roadmap elements impact on the design): an analysis base on multi-objectives optimizations will be proposed to link stakeholders expectations and the critical elements of the proposed case study (i.e. defining elements impact on the design, see “*Prioritization Studies*” phase). Outlining elements impact on design means define which elements can be considered enabling, which ones are enhancing and which ones are not important for the case study. Being the roadmapping process an iterative process, “nominal” values can be defined in a first attempt. In a first attempt, elements impact on design can be imposed at “enhancing” for all the elements, being the worst condition to have no differences between them (i.e. no preferable path exists).

Having defined for each group of elements the enabling, enhancing and not important ones, the final labels have been obtained combining this information through a three-valued logic (Figure 48). In particular, using an AND operator and considering enabling elements as “true”, not important elements as “false” and enhancing elements as “unknown”, it is possible to define required combinations of elements (i.e. true), applicable combinations (i.e. unknown) and not applicable combinations (i.e. false).

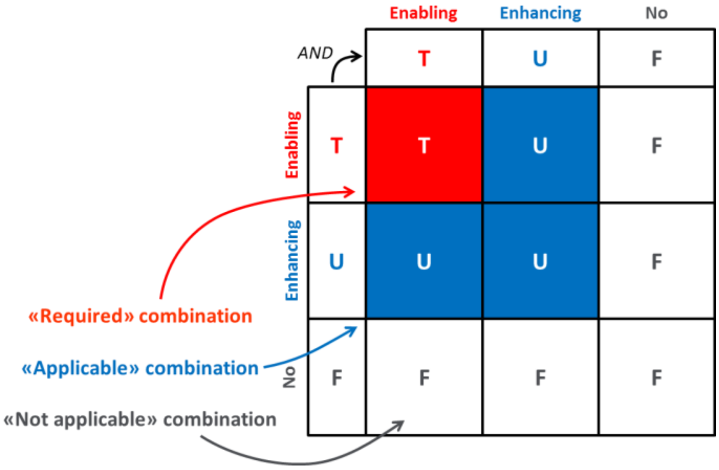


Figure 48: Definition of the applicability map labels through a three-valued logic.

The only Applicability Analysis that not considers the labels is the one between MCs and technologies. Indeed, many of the missions considered are proposed or relatively new and for this reason strictly proposed to solve the Technology Maturation Plan for new technologies. For this reason, an analysis of the modes of operations active in every new MC and an analysis of which technologies are effectively active in every mode is there exploited to define if it is possible to use a specific technology in a specific MC, without weighting this combination. The choice between the whole list of possible MCs and the ones that will be really used for the TRL increase path definition is done through a prioritization of both the MCs and the technologies.

Eventually, it is worth mentioning the applicability of technologies onto technologies. This analysis is directly related to the IRL, the TRL and applicability of TAs/technologies onto BBs. In order to simplify the data insertion for a generic user and considering the difficulty in estimating IRL value only knowing basic technologies performances or their description, a simplified and objective method to obtain this applicability map is proposed. Considering the IRL definitions (Sauser, 2009), is possible to define a scheme to relate current TRL for two technologies and the presence required and applicable combinations with BBs (considering the BBs related to both the technologies) (Figure 49).

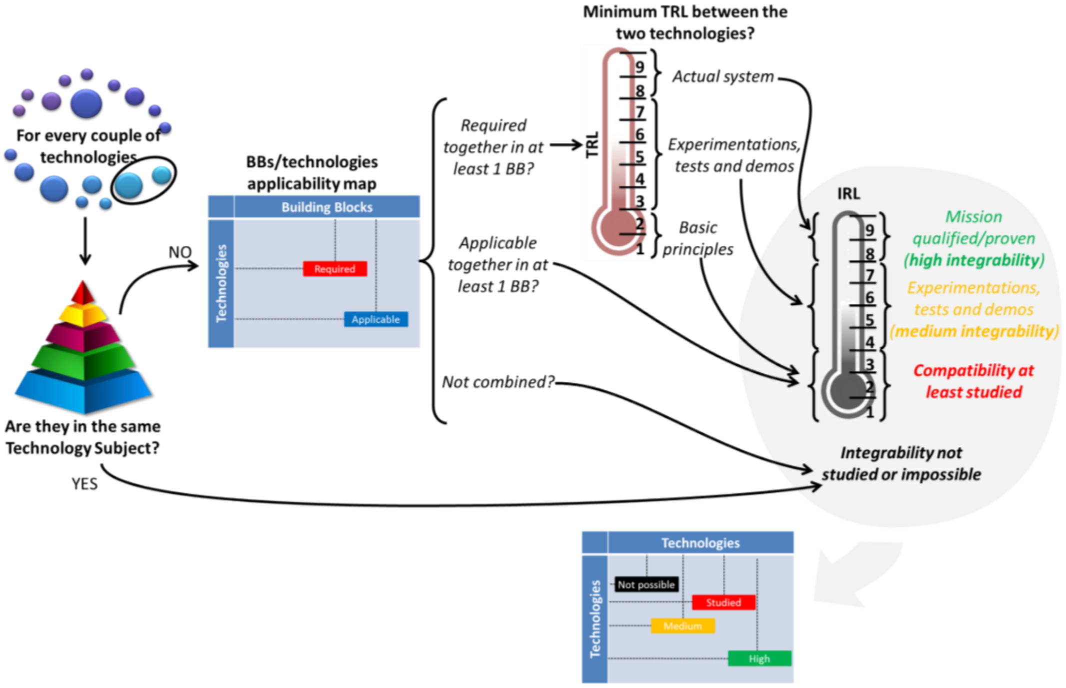


Figure 49: Technologies incompatibility analysis and new mission concepts proposal.

Based on this last applicability analysis it is possible also to check the MCs list for incompatibilities in the technologies selected for it. In particular, it is possible to impose the following rules:

- To propose new technologies in under approval MCs, each new technology has to be at least at a “high integrability” level with all the technologies required for that MC;
- To propose new technologies in potential MCs (i.e. in “potential future concept studies” sub-category), each technology has to be at least at a “medium integrability” level with all the technologies with a higher priority level and applicable in that MC.

In case of an incompatibility in an under approval MC, the new technology has to be considered not applicable for this MC. On the contrary, in case of an incompatibility in a potential future concept study, the MC has to be doubled considering as applicable in the first MC the technologies with a higher priority and in the second MC the technologies with lower priority. Finally, for technology maturation activities, one technology at time is considered and, for this reason, no incompatibilities have to be checked.

3.3.3. Sensitivity Analysis

A "*Sensitivity Analysis*" follows the Applicability Analysis to weight the reciprocal link importance and to optimize the results obtained on the basis of market and stakeholders' needs and to verify the results obtained till now (Cresto Aleina, 2017a). Decision Analysis is the main discipline exploited, to size correctly the elements applicability, considering stakeholders needs.

In this phase, required, applicable and not applicable are not only considered as "labels" but are also weighted through sensitivity analyses in such a way to describe clearly the stakeholders' expectations. For example, a first set of weights is defined and optimized by the methodology itself to have the parameters related to these weights in a desired range and with a correct minimum distance between them. In particular, the following parameters can be considered: *pseudo-TRL*, the sum of the different weights related to a single technology over the different OCs (*most required/applicable between the OCs*) and the sum of the different weights related to a single technology over the different BBs (*most required/applicable between the BBs*) (Cresto Aleina, 2016c). These values can be used as basis for the sensitivity analysis and are related to a quantification of how much a specific technology can be required or applicable to other types of elements. The only weight that can be fixed is the "not applicable" one that has to be 0.

In order to optimize the three parameters, a user might be interested in branching out the values for the three parameters. Every combinations of weights is applied to the applicability maps, varying both the "applicable" weight and the difference between this weight and the "required" one between 0 not included and a maximum value included such as 2 (with a step known for simplicity). At this point, looking at the results achieved is possible to find vectors of the three parameters previously listed (one for each weight combination and for each parameter). For each vector, it is possible to define the minimum and the maximum differences between the values. Analysing how the three parameters listed above vary according to the different combinations of weights, it is possible to choose the combination able to balance all the parameters and able to branch out them. For how they are defined usually weights combinations that gives an average of minimum and maximum difference are the best option. Indeed, while pseudo-TRL is at its optimal condition for low applicable label weights and for high required label weights, the other two parameters are in the opposite condition.

3.3.4. Prioritization Studies

Another phase that exploits only Decision Analysis tools and theories is the "*Prioritization Studies*" phase. The main purpose of this phase is to rank the elements (especially technologies and missions), in order to suggest and weight preferable paths to be followed in the roadmap definition. The Prioritization Studies are a particular type of trade-off study: Decision Analysis is a crucial support for decision makers in this phase to derive optimal solutions in a roadmapping process that is usually characterized by difficult decisions for the high number of stakeholders and the multiple (and sometimes conflicting) objectives. Two purposes or levels of detail are there possible (Figure 50).

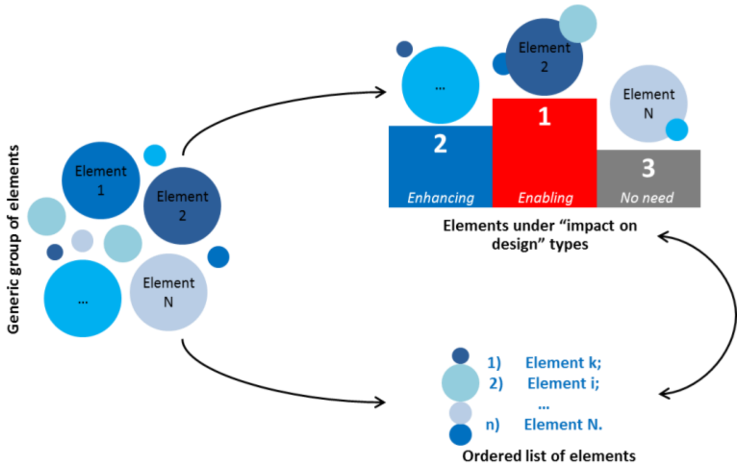


Figure 50: Scheme of the main purposes of the prioritization process.

On one side, it is possible to categorize qualitatively technologies in types of priorities or in levels of impact over the design. In this case each elements have to be studied to define if enabling (i.e. critical elements for the Research Study Objective achievement), enhancing (i.e. elements able to improve the Research Study Objective achievement but that are not required for it) or not important. On the other side, it is possible to obtain a more quantitative prioritization of the elements defining a ranked list. Both cases refer to the stakeholders' expectations and strategies.

3.3.4.1. Roadmap elements impact on design analysis

The definition of elements impact on design is important not only to have a draft ranking of the elements, but also to have a clear view of critical elements for the case study design. As previously said, defining elements impact on design means define which elements can be considered enabling, which ones are enhancing and which ones are not important for the case study and an analysis base on multi-objectives optimizations is there applied to link stakeholders expectations and the critical elements of the proposed case study.

In a first attempt, elements impact on design can be imposed at "enhancing" for all the elements, being the worst condition to have no differences between them (i.e. no preferable path exists). After the first iteration, enough data exists to define elements impact on design and iterate for the final result. While for BBs and OCs this process can be simplified to reduce the stakeholders influence on the results, the technologies have to be strictly related to the stakeholders needs. The reason of this is in the strict link between technologies and market needs to be sure to be innovative in the final roadmap definition, while the other elements are more driven also in the derivation by the applied Systems Engineering approach and for this reason are more general. In addition, critical technologies are the ones that enable the mission objectives, not only from a technical point of view but also from political and social point of views: enabling, enhancing and not important technologies have to be identified also through criteria coming from these areas. Stakeholders coming from many different areas (e.g. final mission needs, political needs, general public needs, economic needs, scientific needs, technological needs) has been analysed in terms of criteria that they can apply, influence and interest in the case study. The results of this analysis give the rational to split the technologies into three different groups (i.e. enabling, enhancing and not important) according to their impact in the case study. To identify technologies impacts on design, the following steps have to be performed (Figure 51):

1. Stakeholders' Analysis to understand stakeholder needs and their influence and interest;
2. Stakeholders' needs become criteria with a certain filter under (or over) which stakeholders do not consider the technologies strategic anymore;
3. Criteria combination to understand which technologies are enabling, enhancing or negligible;
4. Identification of the criteria combination able to optimize a certain number of FoMs;
5. Identification of the enabling, enhancing and not important technologies according to this combination.

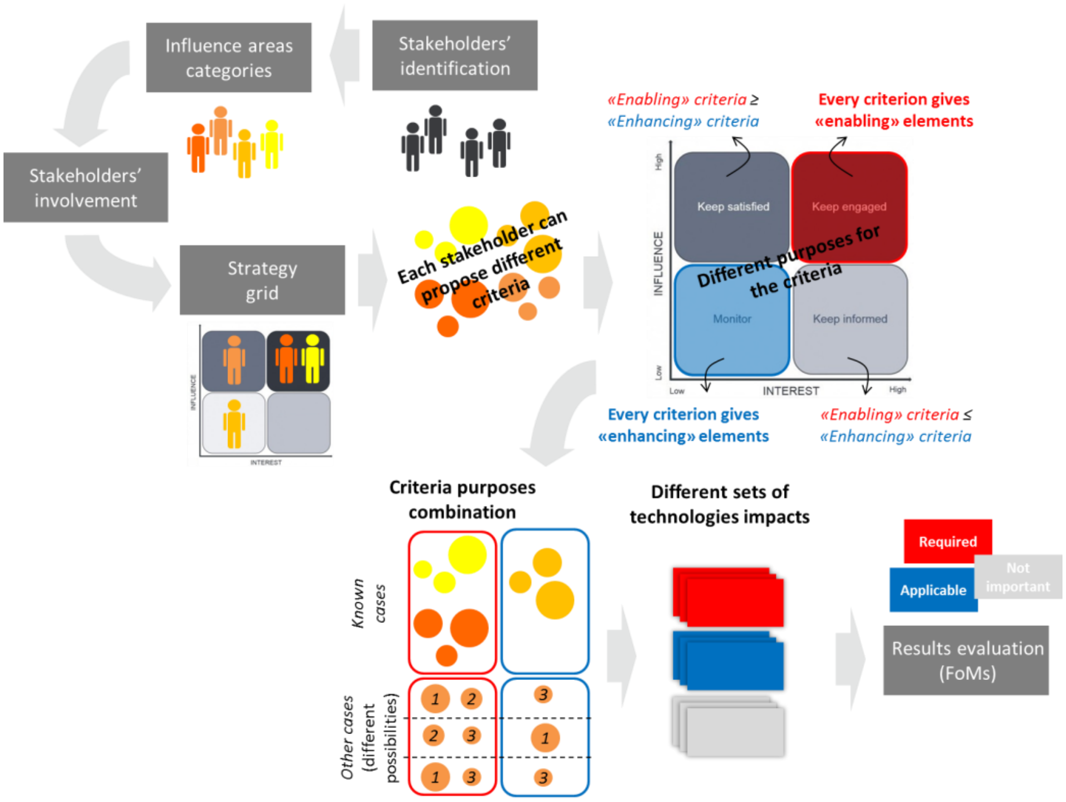


Figure 51: Technologies impact on design evaluation scheme.

To solve the point number 4, it has to be performed a trade-off analysis based on a certain number of FoMs and the following three ones are considered and evaluated on the basis of the first attempt of impact proposed previously (see paragraph 2.3.4.1 for more details): TRL cost-effectiveness (FoM_1), average costs increase (FoM_2), total probability of failure (FoM_3). Indeed, defining the TRL and using the definition of AD2 and its link with the risk analysis, is possible to define FoM_2 and FoM_3 (see paragraph 2.3.6 for details), while FoM_1 can be derived through (2.2). In addition, assuming two coefficients i and j in ℕ criteria and FoM have to follow this rule to ensure results validity:

$$FoM_i \neq f\left(criterion_j\right) \tag{3.1}$$

Finally, the following rule is considered to choose the criteria combination to apply:

$$TOT1 = K\frac{FoM1(1 - FoM3)}{FoM2} \tag{3.2}$$

Where K is a coefficient obtained summing the number of criteria that creates enabling technologies multiplied by 2 and the number of criteria that creates enabling technologies multiplied by 1.

This analysis for BBs and OCs is reduced: a classical multi-objective optimization is used characterize these two groups of pillars (i.e. a Pareto front analysis). The main criteria to be satisfied in determining OCs and BBs impacts on design are derived from technology roadmap definition. Indeed, it is clear that that a roadmap will have to foresee the main future innovations, without considering risky or impossible design solutions. For this reason, each OCs and BBs will be studied considering as criteria (i.e. objectives to reach):

1. *To have solutions with an higher competitiveness* (e.g. if this element is strategic or not in the current scenario);
2. *To have less risky solutions* (e.g. if this element is currently present on the market or if this is not).

In evaluating these criteria, some considerations are required. First, it is possible to define both criteria for each trade-space variable (BBs and OCs) and, then, it is possible to compose each criterion following how OCs and BBs are composed. Secondly, both criteria have to be maximized to optimize the results. Finally, in order to discard any OCs and BBs (to consider them not important) it has to be considered a constraining point to suggest a hypothetical minimum optimal solution: indeed, looking at how the roadmap is defined it is important to have solutions that certify at least a minimum level of competitiveness (first objective) and low risk (second objective). For example, it is possible to impose the presence of at least a competitive element in every solution and to have a risky level equal to the minor 1 (keeping out the possibility to have no risk). Thanks to this, it is possible to define a two-dimensional Pareto front (Gollub, 2009) considering in this front all points that are not dominated by other and to select enabling, enhancing and not important OCs and BBs (Figure 52).

Finally, MCs are not characterized considering that they are more related to the budget and the schedule and are an important brick in the TRL increase path definition: constraining this pillar to an additional characterization can led to mistakes in the final evaluation.

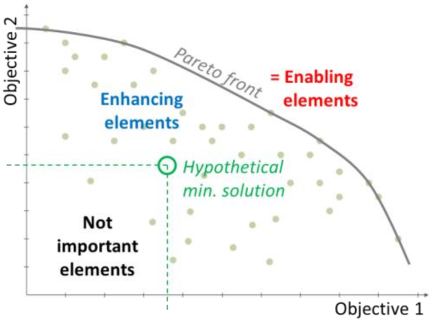


Figure 52: OCs and BBs impact on design analysis.

3.3.4.2. Technologies ranking

Technology prioritization methodologies have been developed in order to provide logical and quantitative instruments to verify choices of prioritization that can be carried out based on important, but non-quantitative factors. Generally, three main steps (Figure 53) can compose a technology prioritization study. Firstly, inputs have to be established, usually from technology roadmaps and roadmaps' elements derivation methods. In this phase, technologies are listed but not ordered according to any ranking criteria. Secondly, prioritization methods and criteria have to be chosen, usually through stakeholders' interactions and trade-off analyses. In this phase is also important to define constraints or FoM that might have an influence on the result: these parameters will have an important role in trade-off and sensitivities analysis in order to size the result. Finally, applying criteria, methods and constraints, an ordered list of technologies can be obtained and can be used as input for technology roadmaps definition, decision makers' analysis and TRL increase path evaluation. According to a general technology prioritization study (Figure 53), prioritization methods, criteria, FoMs and constraints have to be chosen, usually through stakeholders' interactions and trade-off analyses. Method and criteria of prioritization have to be defined at the very beginning. In many methods, the criteria and the method weights and rules are already established through stakeholders' interviews.

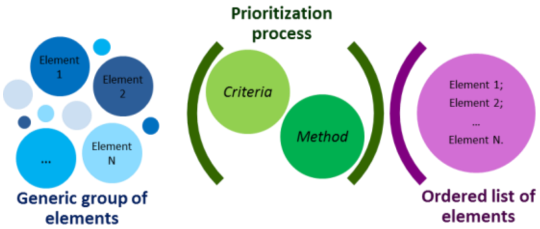


Figure 53: Prioritization studies generic scheme.

Applying the same criteria, stakeholders, their categorization, their influence and interest on the project already applied before, it is possible to rank the technologies. The main difference from before is the application of these criteria not on a first attempt of applicability maps and applicability labels weights, but on the final ones. Having defined the criteria to apply is necessary to define a way to apply them on the case study, i.e. a prioritization method. The final method proposed is a hybrid version of a prioritization matrix (Figure 54), where decision tree is proposed to find every possible criteria combination and choose the optimal solution (McNamee, 2001; Cresto Aleina, 2017e). The criteria combinations are created considering that every possible combination has to be considered and that criteria that are not compatible between them or that use in opposite way the same parameter cannot be used in the same combination. Finally, combinations of different number of criteria have to be included.

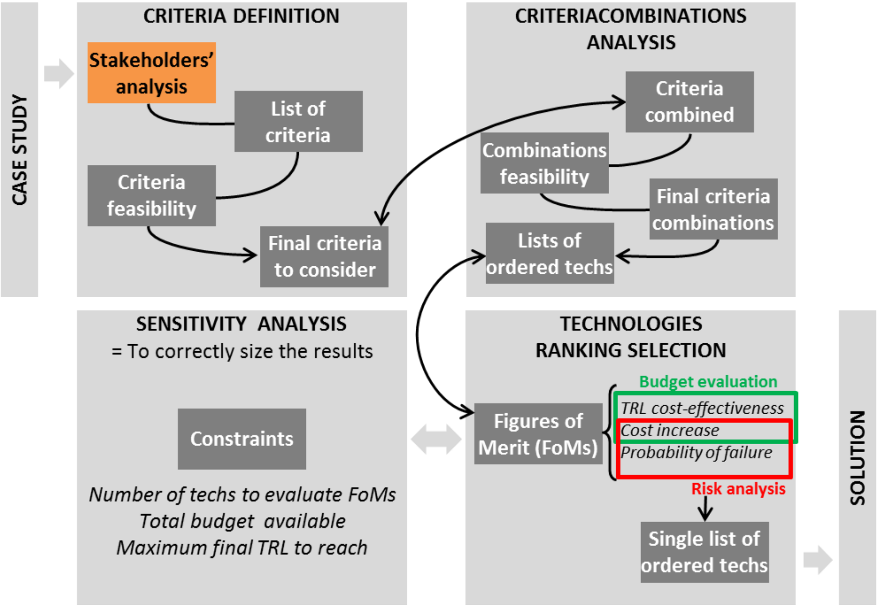


Figure 54: Generic scheme of the proposed methodology for technology prioritization.

Also the same FoMs applied in the previous part are employed at this point to compare each criteria combination results. It can be easily understood that if the FoMs are independent from the order of the technologies in a list-. For this reason the number of technologies at which evaluate them has to be limited to a number that is less than the total number of technologies involved. Indeed, being these technologies the same for all the criteria combinations, the three FoMs will be the same for the entire list on technologies and for each criteria combination. In order to propose an optimal number of technologies to constraints the technology ranking selection, a sensitivity analysis has to be performed varying this constraint and looking at the three FoMs trends.

Finally, the following rule is considered to find the optimal solution is again (3.2), where K is a coefficient evaluated through the following equation:

$$K = \sum_{i=1}^{N} \frac{s_i}{p_i} \tag{3.3}$$

Where N is the number of criteria in the combination, i is a generic criterion inside the combination, p_i is its position inside the combination and s_i is the weight of the stakeholder asking for it. In particular, s_i is defined considering a weight of 1 for a stakeholder to “monitor”, 2 for a stakeholder to “keep informed”, 3 for a stakeholder to “keep satisfied” and 4 for a stakeholder to “keep engaged”. In case more than one best solution is provided applying (3.2), it is necessary to compare the ordered list of technologies. In case of the same list is achieved as result, for simplicity the combination that involves fewer criterions or with less approximation is the one chosen. On the contrary, the FoMs have to be additionally compared at the first different technology.

3.3.4.3. MCs ranking

Also the MCs list has also been ranked to proceed with the planning definition. Looking at the method employed to define the MCs list, it can be seen that the missions are already defined directly looking at market current scenario and at stakeholders’ needs. For this reason and in order to not consider twice the same requirement, the mission prioritization considers proposing solutions that are not so risky or expensive to not be applicable in a near or far future and to propose innovative solutions. MCs have been ranked according to:

1. *Minimizing the required budget*;
2. *Minimizing the vicinity to the Earth surface* (i.e. reducing costs);
3. *Minimizing the number of Modes of Operations* (i.e. reducing costs, minimizing the number of MCs required to cover every functionality);
4. *Maximizing the number of technologies* (i.e. reducing costs, minimizing the number of MCs required to cover every technology in the list);
5. *Minimizing the minimum TRL required* (i.e. being sure to propose missions with a sort of time progression).

The criteria choice has the objective to give higher priority to the missions near Earth and with the higher number of technologies at least applicable in order to minimize costs and the final number of missions required for the roadmap. For example, technology maturation activities are the ones with a higher priority being the less expensive and being made in laboratory. Lower priority is given, on the contrary, to operative missions, being not only not on ground, but also the missions with a higher TRL required.

3.3.5. Planning Definition

For this purpose, the outputs from all the previous phases are crucial for the "*Planning definition*" phase, where missions and technologies are combined to define the roadmap both in term of missions that have to be performed to reach the technological maturity and in term of schedule and resources to match the programmatic requirements. For this purpose, the methodology proposed is able to suggest an optimal TRL increase path combining the technologies' and the MCs' priorities with a budget analysis and a check for technologies compatibilities inside the same mission (Cresto Aleina, 2017a).

In particular, it is possible to propose a planning following these steps:

1. *Budget analysis* to prune the list of technologies on the basis of the available budget (i.e. being sure to consider in the planning only the technologies on which it is possible to spend on);
2. *MCs selection*, imposing 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*, combining the final MCs with a time reference.

In the budget analysis, data that have to be known are the available total budget and the financial resources required to perform each TRL transit for each technology. Thanks to the technology prioritization, it is possible to distribute the available budget between the technologies starting from the technologies with a higher priority and looking at the best way to spend all of it. On the contrary, MCs priorities are important also in the MCs selection, where the MCs to propose in the final planning are selected starting from the lower TRL to be performed and selecting for each TRL the MCs with a higher priority able to perform them. At this point, it is required to know the minimum TRL of the technologies applied. In proposing a planning this parameter is important, because lower TRL MCs will have to be performed before higher TRL ones and MCs have to wait that all the technologies combined in them will reach the desired TRL. Assuming no waiting time between each MC is possible to propose a planning (Figure 55).

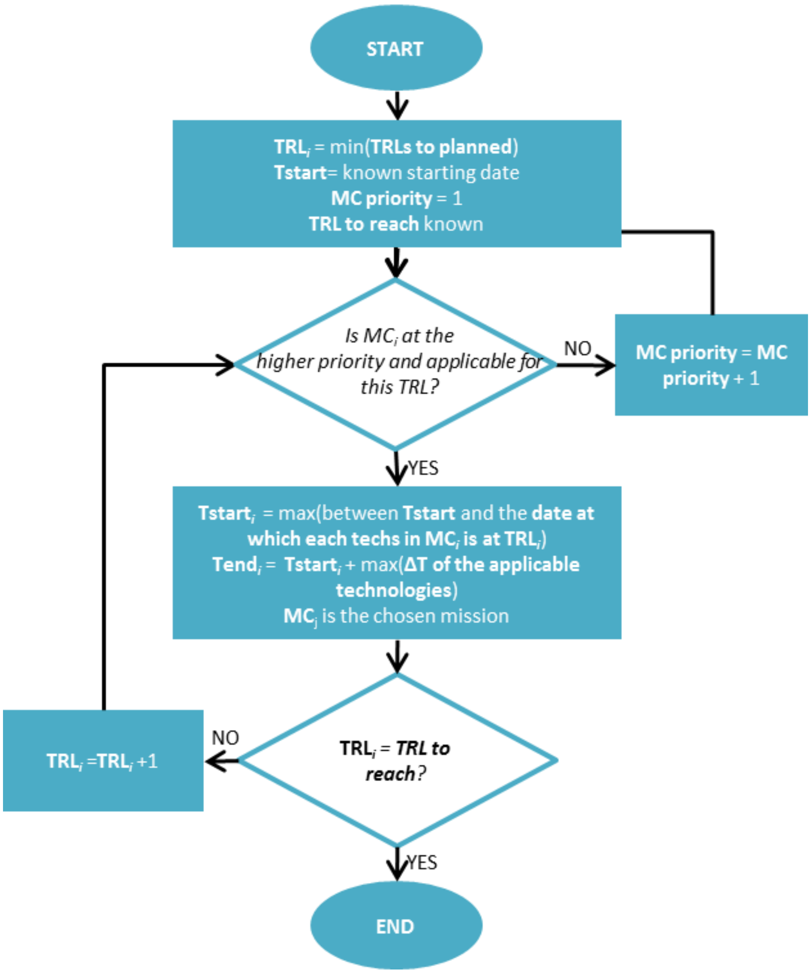


Figure 55: Schedule definition process.

Looking in literature (van den Abeelen, 2016), it is usual to suppose 10 years for a nominal schedule in space exploration projects (i.e. for a complete study from TRL 1 to TRL 9). Even if this is known that, it is unusual to know how much time it last each MC or how much time it takes a single technology to perform each TRL transit. At the same time, it is difficult to find also data about the financial resources required to perform each TRL transit for each technology.

To simplify the data definition, it has been defined a relationship between technology maturation (i.e. the TRL), the programme schedule supposing nominal conditions and how the available budget or CaC has to be distributed (Cresto Aleina, 2017b). In particular, starting from the cost levels described in (Mankins, 2009) for each TRL transit and comparing them with the cost levels present in (ESA, 2015b) (Figure 56 on the left), it is possible to see that they have quite the same trend till TRL 6. It has to be said that in ESA roadmaps the CaC only refers to the technology and many costs related to the missions are not included for strategic reasons: above TRL 6 mission costs play a significant role. In addition, (Mankins, 2009) only defines costs at generic ranges (i.e. low, medium, high), without providing numbers. Normalizing for each technology each TRL transit for the total CaC of that technology and assuming to have the same ratio for the cost levels as in (ESA, 2015b) and in (Mankins, 2009), is possible to define how statistically a generic technology CaC has to be distributed between the different TRL transit (Figure 56 on the right). Performing the same exercise but using as reference experts opinion and literature (Cresto Aleina, 2017a; van den Abeelen, 2016; Bayer, 1995), it is possible to achieve the same results but in the case of an hypersonic space transportation and re-entry system (Figure 57).

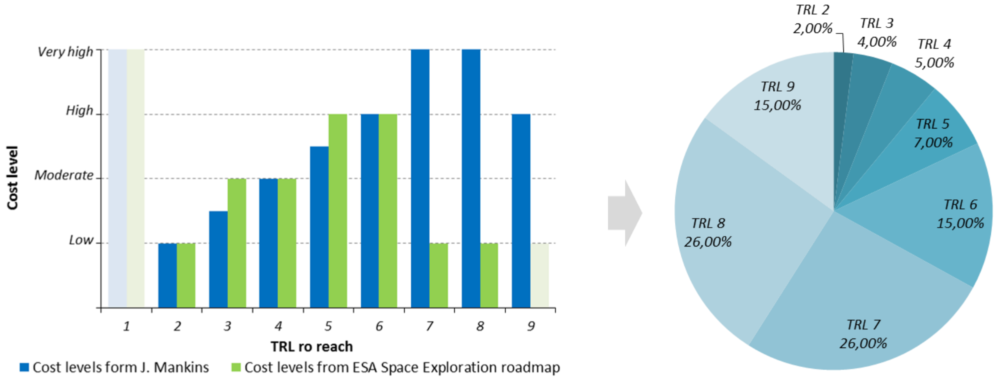


Figure 56: Generalized expectations for the CaC distribution between different TRL transits for a space exploration system.

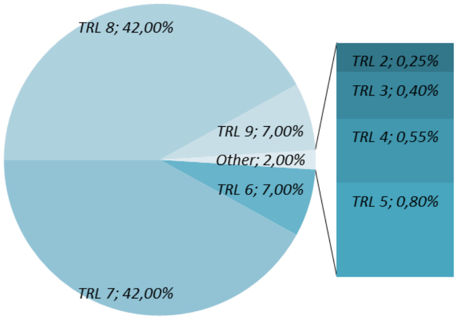


Figure 57: Generalized expectations for the CaC distribution between different TRL transits for a hypersonic space transportation and re-entry system.

In order to perform a similar exercise to propose how a total timeframe can be divided into the times to perform each TRL transit, (Copeland, 2015) can be used as reference. Indeed (Copeland, 2015) has studied the data present tin database of the DoD, proposing a relationship between TRL and US DoD life-cycle phases (Figure 58). From this analysis, it is possible to define levels for the timing between different TRL transits. Combining these levels with date present in literature (Guerra, 2008; ESA, 2015b) it is possible to propose how a total timeframe can be divided into the times to perform each TRL transit (Figure 59). This distribution, for the generality of the data employed, is true for both a space exploration system and a hypersonic space transportation and re-entry system.

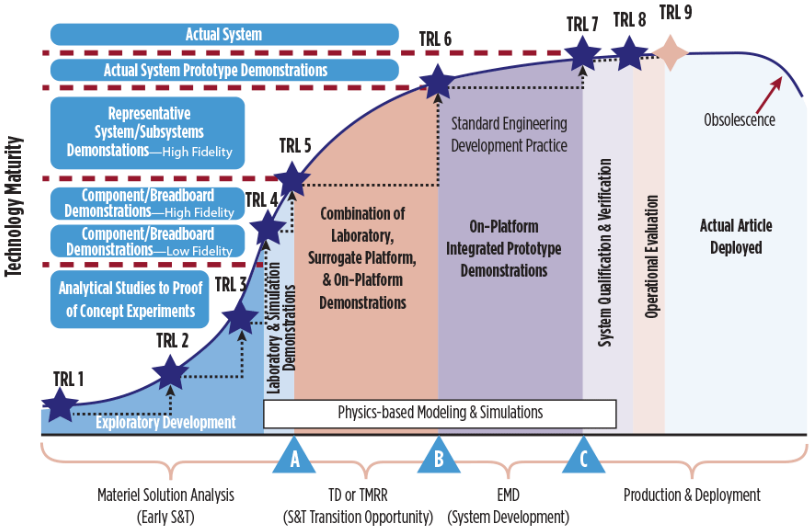


Figure 58: US DoD life-cycle phases and technology maturity according to (Copeland, 2015).

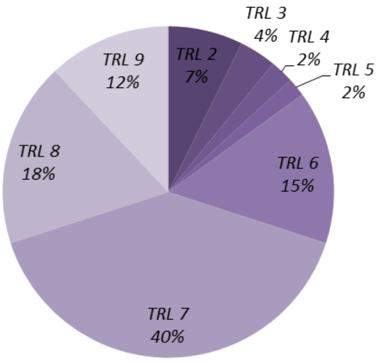


Figure 59: Generalized expectations for the timeframe distribution between different TRL transits.

3.3.6. Results Evaluation

Finally, with “*Results Evaluation*” the roadmap can be verified, proposing it to expert for their review or update. Indeed, once this process is completed, all data need to be updated and (at least periodically) reviewed. This implies that the elements lists have to be integrated with innovative or future solutions, the elements features can change and their maturity increases. This is an iterative and recursive process aimed at outlining an optimized Technology Maturation Plans and at providing it to the final users.

3.3.6.1. Draft Risk Analysis

At the beginning of the design activity, only limited data on required technologies may be available and risks can be estimated only at a high level. For this reason, a relationship between TRL and AD2 is proposed, based on the comparison between the target to reach and the target for which a technology is designed (Cresto Aleina, 2017e) (Figure 60). A direct link between AD2 and risks can, therefore, be established (see paragraph 2.3.6 for details) and through a risk matrix it is possible to define a relationship between likelihood of failure and consequences for safety, technical or cost and schedule issues (Alcorn, 2009).

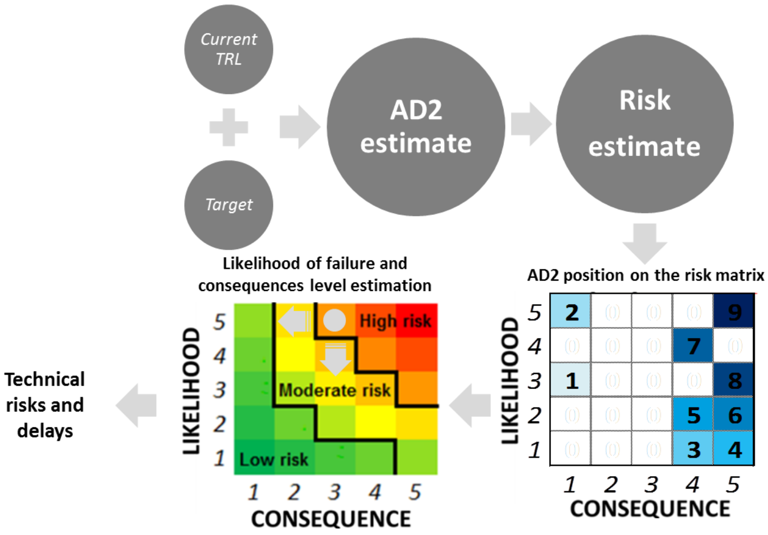


Figure 60: AD2 and TRL relationship scheme.

Even if this analysis has to be performed in the “*Roadmap elements definition and characterization*” phase or in the Roadmap elements impact on design analysis (see paragraph 3.3.4.1 for details) to characterize the technologies, it represents only a first iteration starting from the state of the art of each technology. The data that have to be achieved at this point refers to the situation potentially achieved at the end of the nominal planning. In addition, it is important to note, in the first iteration, the consequences level: indeed, according to (Alcorn, 2009), this level can be referred to a maximum allocated costs increase percent. Knowing this percent for each technology it is possible to estimate an expected allocated costs increase and expected delays for each technology (i.e. technological over-costs and delays).

3.3.6.2. Delays and over-costs estimation

Once defined the “nominal” schedule it is possible to derive on a statistical basis possible delays or over-costs. In defining a SoS (or a megaproject), it can be noticed that a SoS is not only related to design activities, but also imply a strong relation with the social, economic and political scenario. In particular, considering as reference PEST (Political, Economic, Socio-cultural and Technological) analysis, some external factors that can have an influence on a design process or on a business and can be can be categorized, indeed, as Political, Economic, Socio-Cultural And Technological factors (Sammut-Bonnici, 2015). For simplicity, it can be assumed in a space exploration context that socio-cultural factors have a negligible direct influence on delays and over-costs: indeed, for how usually SoSs are structured it these factors do not have a direct influence on the design process, but they have an influence on the other factors. In addition, different factors have a different influence on delays and over-costs (Figure 61).

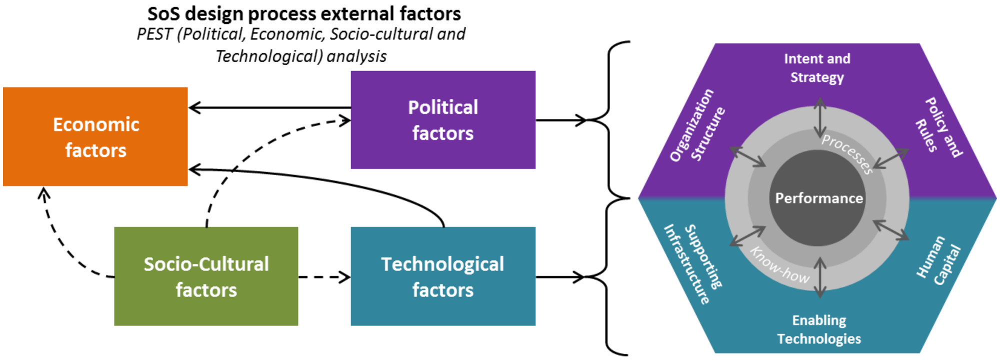


Figure 61: Burlton Hexagon (Burlton, 2011) and PEST analysis external factor relationships (Sammut-Bonnici, 2015).

While knowing the AD2 it is possible to derive delays and over-costs related to technological issues (Alcorn, 2009), this is not true for the other two remaining factors (i.e. political and economic factors). According to the Burlton Hexagon (Figure 61), every organization has to face with technological and political factors that cooperating can obtain an effective result (Burlton, 2011). In particular, political factors can be divided into 3 sub-categories (i.e. organization structure, intent and strategy, policy and rules) and the same for the technological factors (i.e. supporting infrastructure enabling technology, human capital). It is clear to understand that every political section can cause a non-technical delay that affects the result also in term of over-costs caused by features of the technological factors. For example, every facility and expertise has to be maintained in case of a delay to proceed with the design once the situation that was causing the delay is solved. Analysing the sub-categories of political and technological factors it is possible to define on one-side delays caused by changes in the political factors and, on the other side, over-costs that these delays cause in the technological factors. These over-costs caused by waiting times can be considered as effects of the economic factors. It is important to note that when the total over-cost value exceeds stakeholders' available financial resources other delays can be created (e.g. waiting for financial resources) or the entire process can be cancelled.

Looking at the three political factor sub-categories is possible to estimate the frequency and the amount of expected delays. In space exploration scenarios in Europe, it is usual to have the following condition, according to literature (van den Abeelen, 2016; Bayer, 1995) and looking ad ESA structure:

- Changes in the organization structure usually happen every 5 years (e.g. new directors' elections) with a delay of 9 years;
- Changes in intent and strategy usually happen every 2 years (e.g. a new ministerial council) with a delay of 3 years;
- Changes in policy and rules usually happen every 7 years (e.g. a change in the standards that designers have to follow such as ECSS standards) with a delay of 1 year.

Appling them to the case study on the base of the nominal schedule, the total amount of delay can be derived and the over-costs related to non-technical issues can be estimated. Over-costs can be produced thanks to the delays to preserve the human capital, the supporting infrastructures and to maintain each technology in a status able to operate during the delay. Indeed, in case of a loss in the current know-how or in the status of the organization means that gaining it again and this is equivalent to the loss of one or more TRL transits.

3.3.6.3. Desired TRL sensitivity analysis

Finally, an additional analysis is then performed, varying the desired TRL value (i.e. one of the stakeholders' inputs on which changes can be proposed to increase resources distribution). This analysis is performed fixing the available budget and looking at the best way to spend it according to the prioritized list of technologies. As expected, if a lower TRL has to be reached by all the technologies, more technologies will be involved in the final roadmap. On the contrary,, the opposite case means including less technologies that will be able to perform more TRL transit.

3.4. TRIS: Roadmap Visualization and Update

As previously explained, in a roadmap a significant role is played by its graphical layout and for a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme EIRMA approach has to be proposed. To analyse possible configurations, a Graphical User Interface (GUI) developed in Matlab® and able to download data from both TREx and a generic MS Office Excel® file has been designed to provide a user roadmap data in a pictorial form (Figure 62). In this GUI, 4 types of maps are proposed and two of them are related to technologies: a bar chart describing technological-oriented roadmaps (Figure 63) and a radar view describing current investing and technological maturity related to a particular Technology Subject (Figure 64). It has to be noticed that, currently, TREx is not able to provide data about OCs for an internal review and, for this reason, these data are currently hidden also in the developed tool.

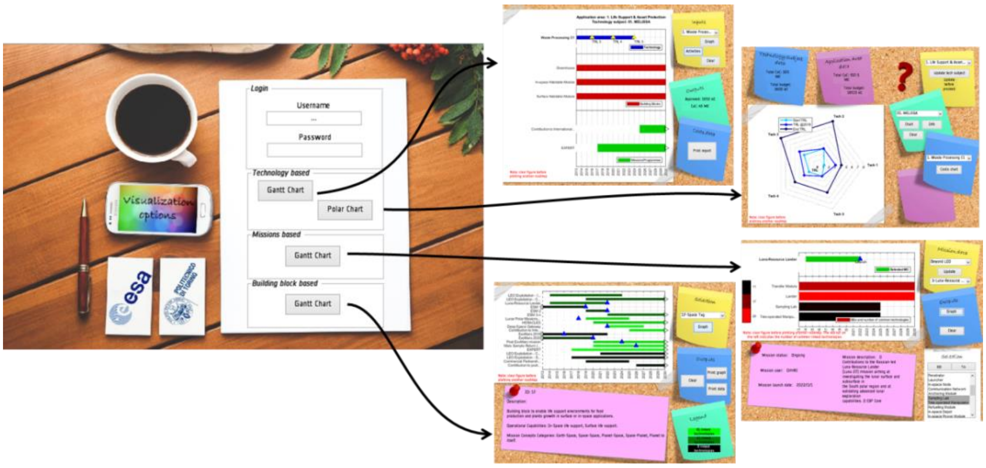
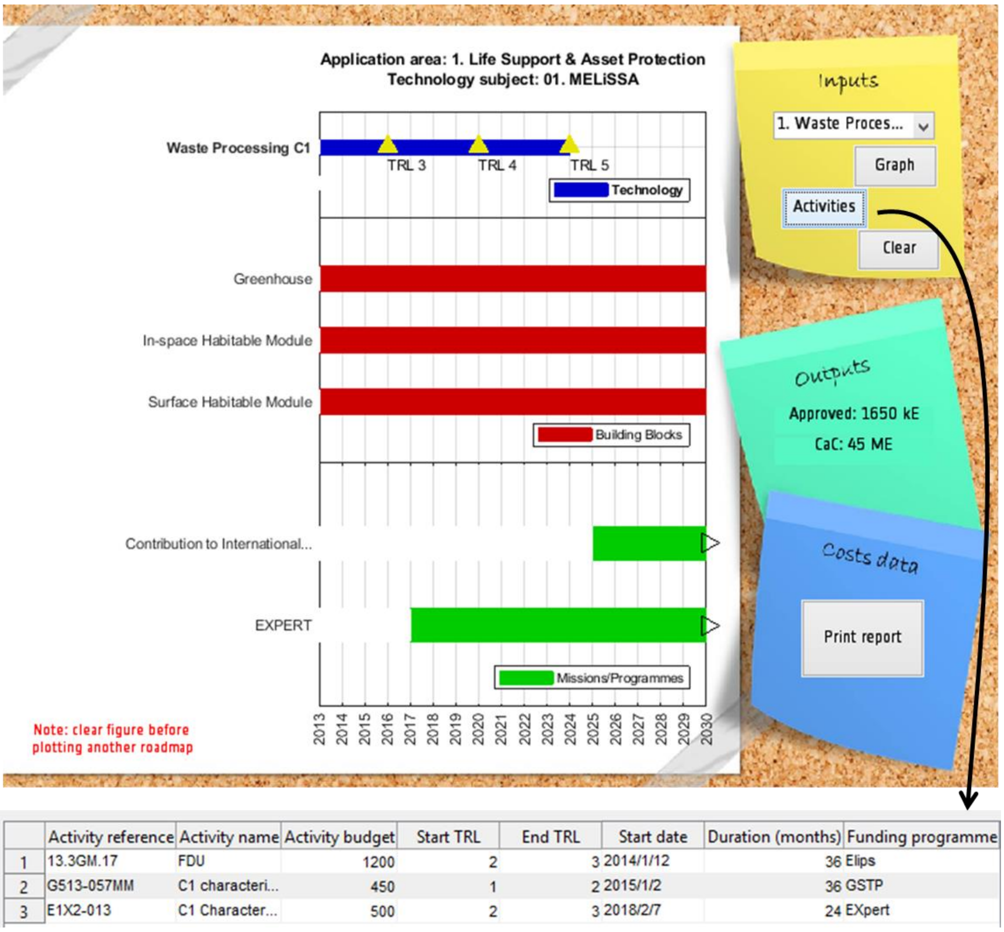


Figure 62: GUI developed for roadmap data visualization.

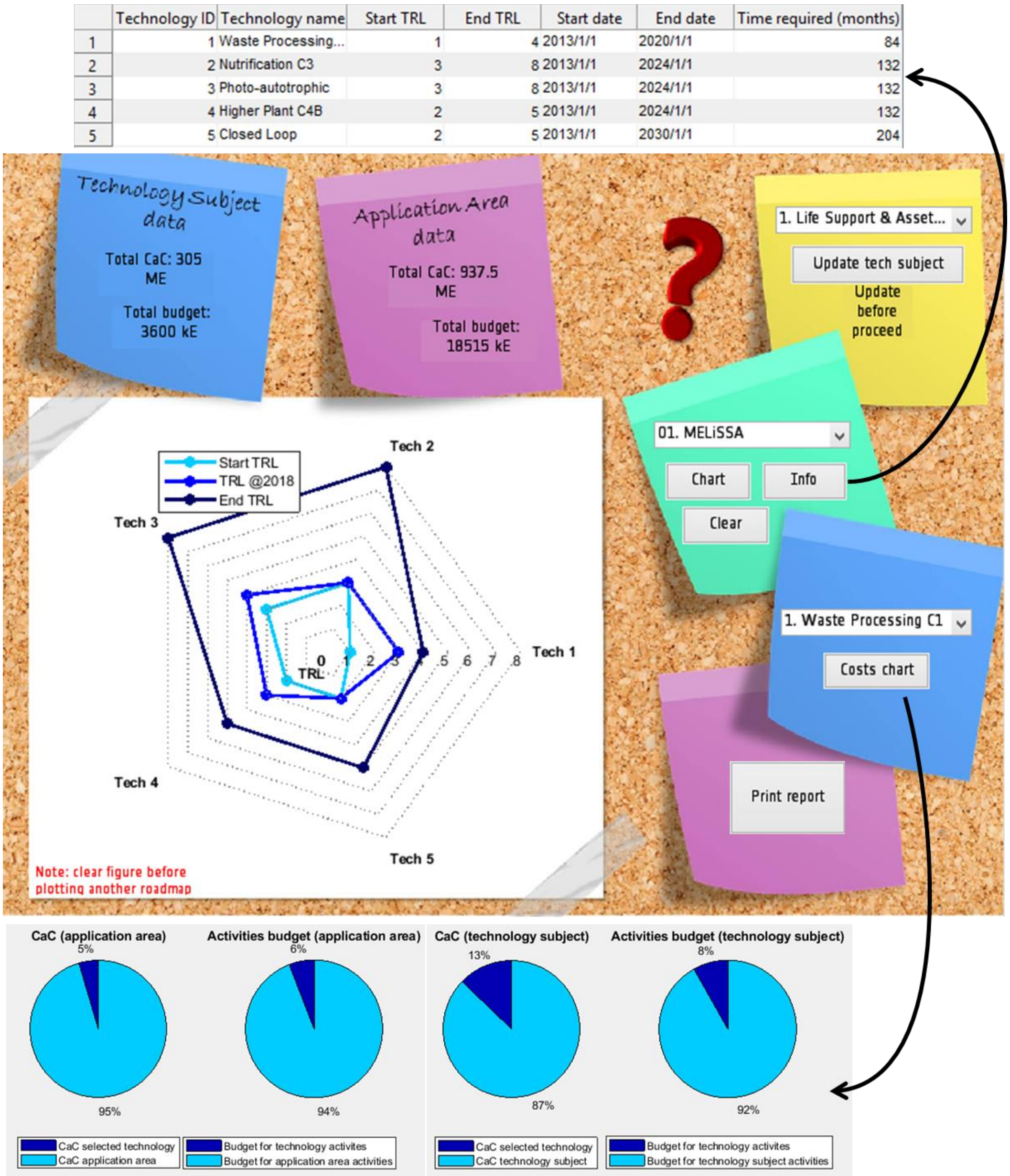


Approved: 1650 kE
CaC: 45 ME

	Activity reference	Activity name	Activity budget	Start TRL	End TRL	Start date	Duration (months)	Funding programme
1	13.3GM.17	FDU	1200	2	3	2014/1/12	36	Elips
2	G513-057MM	C1 characteri...	450	1	2	2015/1/2	36	GSTP
3	E1X2-013	C1 Character...	500	2	3	2018/2/7	24	EXpert

Figure 63: Bar graph roadmap visualization example.

Different is the case of “reverse roadmaps” (ESA, 2015b), i.e. roadmaps that focus on elements that are different from technologies. Being the main source of data TREx, it has to be said that not all the links between elements are provided and for this reason only two types of reverse roadmaps has been tried. A first type of map focus on BBs (Figure 65), providing a bar chart able to describe for each BB the links with MCs and technologies. A second type of “reverse roadmaps” is related to MCs. For MCs, it is true that the link with time is important and it has to be shown, but if the purpose of a roadmap is to show how the different elements are related between them some considerations have to be done. Indeed, it has to be said that TREx is a database that provides data about technologies and, for this reason, every link provided between different elements is with technologies: no data are provided of links between MCs and BB, for example. For this reason, a type of bar chart that can be studied for MCs-based roadmaps needs more data, such as the BBs related to a specific mission (Figure 66).



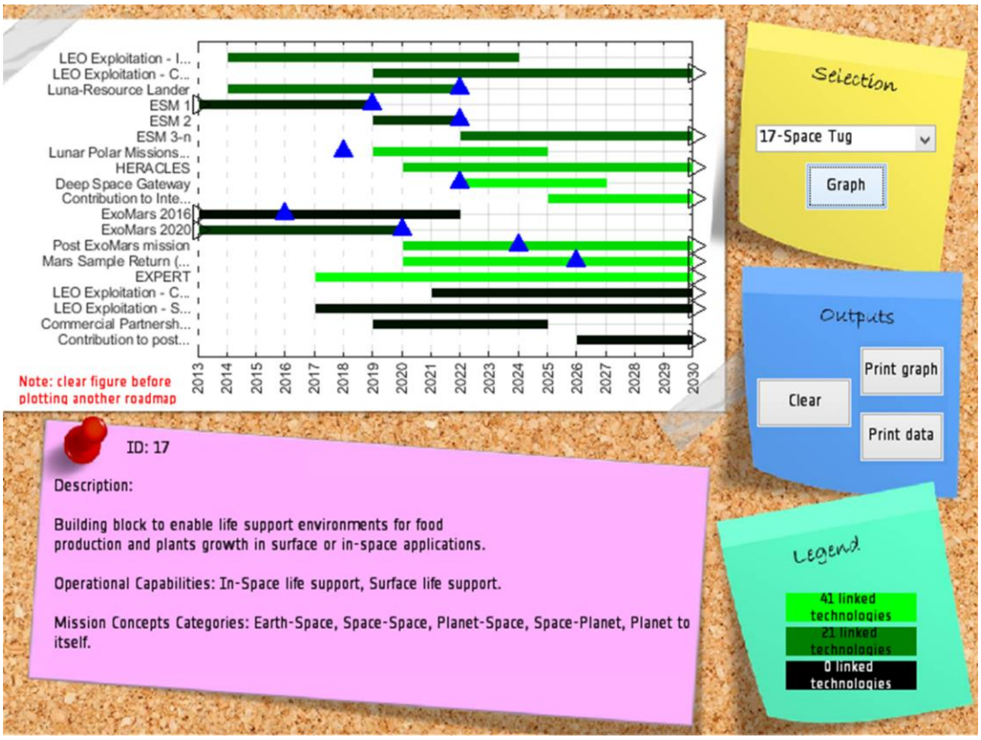
	Technology ID	Technology name	Start TRL	End TRL	Start date	End date	Time required (months)
1	1	Waste Processing...	1	4	2013/1/1	2020/1/1	84
2	2	Nutrification C3	3	8	2013/1/1	2024/1/1	132
3	3	Photo-autotrophic	3	8	2013/1/1	2024/1/1	132
4	4	Higher Plant C4B	2	5	2013/1/1	2024/1/1	132
5	5	Closed Loop	2	5	2013/1/1	2030/1/1	204

Technology Subject data
Total CaC: 305 ME
Total budget: 3600 kE

Application Area data
Total CaC: 937.5 ME
Total budget: 18515 kE

Figure 64: Radar graph roadmap visualization example.

Once defined the roadmap, an important phase is the data update and review. Indeed, with time, pseudo-TRLs advance, mission scenarios progress and technologies TRLs increase. In addition, the properties of the different roadmap elements 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 aimed at optimizing the final roadmap and at keeping it updated.



Note: clear figure before plotting another roadmap

ID: 17

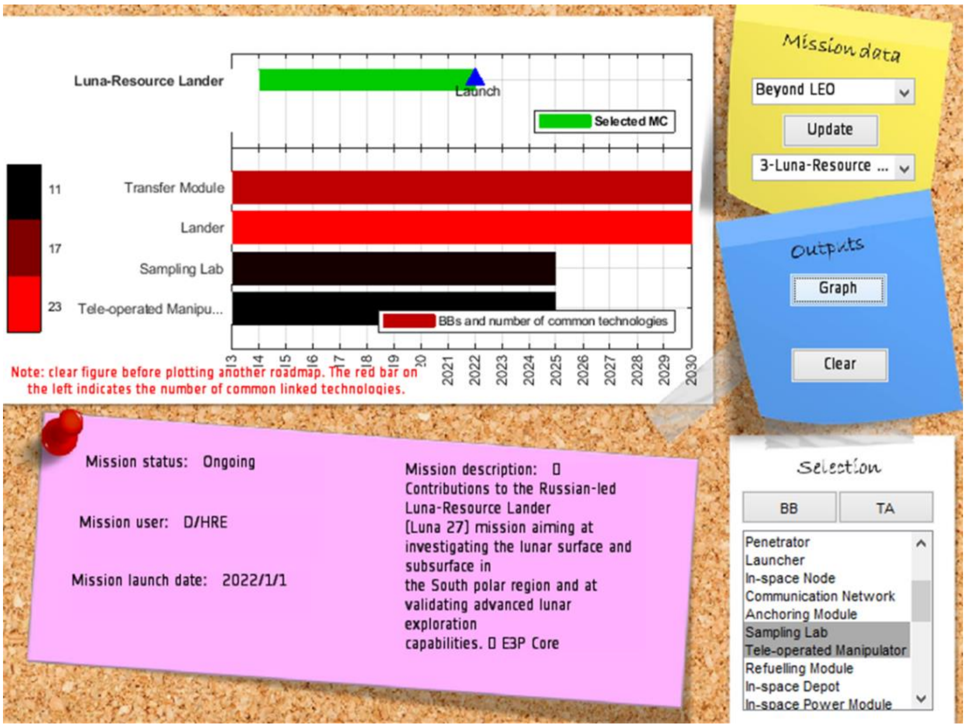
Description:

Building block to enable life support environments for food production and plants growth in surface or in-space applications.

Operational Capabilities: In-Space life support, Surface life support.

Mission Concepts Categories: Earth-Space, Space-Space, Planet-Space, Space-Planet, Planet to itself.

Figure 65: BB-based roadmap example.



Note: clear figure before plotting another roadmap. The red bar on the left indicates the number of common linked technologies.

Mission status: Ongoing

Mission user: D/HRE

Mission launch date: 2022/1/1

Mission description: □
Contributions to the Russian-led
Luna-Resource Lander
[Luna 27] mission aiming at
investigating the lunar surface and
subsurface in
the South polar region and at
validating advanced lunar
exploration
capabilities. □ E3P Core

Figure 66: MC-based roadmap example.

3.5. Highlights

- ✓ Thanks to all the studies performed, a final methodology based on Systems Engineering, Program Management and Decision Analysis theories and tools can be proposed able to derive strategic planning in the field of a mission-oriented roadmap describing a SoS in the context of an ongoing large-scale collaborative programme: TRIS;
- ✓ A certain number of preliminary activities have to be performed before starting the roadmapping activity also in applying TRIS, to define the analysed SoS and its features;
- ✓ TRIS is composed by 6 phases: Roadmap elements definition and characterization, Applicability Analysis, Sensitivity Analysis, Prioritization Studies, Planning Definition and Results Evaluation;
- ✓ TRIS is an iterative and recursive process to support roadmap update and management: the elements lists have to be integrated with innovative or future solutions, the elements features can change and their maturity increases.

Chapter 4

TRIS Application: Hypersonic Space Transportation and Re-Entry Systems

A technological roadmap for hypersonic and re-entry transportation systems can be seen as the best answer to the current lack of common and shared vision that is dramatically hampering the development of this field of space engineering. 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 (Tumino, 2008) has to be mentioned. It has 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 are even more compelling in recent years.

Starting from the definition of a roadmap for hypersonic space transportation and re-entry systems, an example concerning the TPS state of the art at the pre-IXV mission era will be considered. This example has the main aim of providing a sort of verification of TRIS.

4.1. Context and roadmap scenario

One of the two main case studies presented is related to the enhancement of all those technologies related to hypersonic transportation and re-entry systems for their strategic importance for space exploration strategies, especially in Europe. Indeed, the mastering of these technologies is mandatory not only for human or robotic space exploration missions, but also to stay competitive in a very innovative and dynamic environment worldwide. In addition, the design of space vehicles has to be strictly related to reliability and safety requirements if applied in manned missions or over inhabited areas and, for this reason, the design of such a system can be a complex activity to be carried out (Hannigan, 1994).

Differently with other nations such as Russia and United States of America (USA or US), Europe has a limited experience on controlled re-entry (e.g. Beagle 2 (Pullan, 2004) or Huygens (Clausen, 2002)) and this is even more true when dealing with humans on board (Cresto Aleina, 2011). It has to be said that in Europe some direct experiences with robotic hypersonic flight exist. For example, in 1998 ESA has flown Atmospheric Re-entry Demonstrator (ARD) (Cazaux, 1995), a capsule that has demonstrated capabilities related to suborbital re-entry. Other examples are Phoenix (Obersteiner, 2001) and Unmanned Space Vehicles (USV) (Russo, 2002; Chiesa, 2005), flight experiments on winged space vehicles landing Guidance, Navigation and Control (GNC). Additionally, with the German Sharp Edge Flight Experiment (SHEFEX) (Longo, 2009; Steffes, 2012) very high Lift over Drag configurations for space vehicles, based on a sharp edged faceted concept, has been investigated. Recently, following a sub-orbital flight path, ESA performed a highly successful earth-atmosphere re-entry flight experiment based on IXV (Tumino, 2008; Haya Ramos, 2015). On the contrary, when dealing with the transport of astronauts, only some heritage is available from past programs (e.g. Future European Space Transportation Investigations Programme (FESTIP) (Kuczera, 1996), Sänger (Kuczera, 1991), Hermes (Trella, 1989), X-38 (Dale Reed, 1997), SHEFEX IXV and Space Rider (Massobrio, 2016), the Inflatable Re-entry Demonstrator Program (IRDT)) (Wilde, 2001).

Recently, commercial private initiatives are under development or are commercializing vehicles capable to perform similar missions also enhancing partial re-usability of vehicle elements (FAA, 2016; NASA, 2014). This is particularly true in the USA (e.g. the XCOR Lynx (XCOR Aerospace, 2012)). This attention from the private sector transforms this in an emerging field in which it is important to be competitive. A comparable initiative is still missing in Europe because costly and risky new technological developments are still left to government-financed projects (Puettmann, 2003), even if some partial private commercial development are present, (e.g. Reaction Engine Limited with Skylon (Varvill, 2004) or Swiss Space Systems (S3) with Soar (Forczyk, 2015)).

In this context, the application of TRIS can simplify the elaboration of technology roadmaps for European hypersonic re-entry space transportation systems, supporting also the definition of a database for hypersonic transportation and re-entry systems. A similar context is again a SoS. Indeed, it is newly a field in which a certain number of mission-oriented programmes are involved, with a certain number of stakeholders also different between them. Also in this case, time and budget are usually high enough to involve in decision-making and design processes necessities and impositions related to non-technical factors (e.g. political, social and economic factors, see (van den Abeelen, 2016) for an example). Finally, it is true also in this case that a common strategic goal exist. In particular, it can be considered as a final goal the achievement in a manned mission of a safe re-entry exploiting hypersonic regimes for civil transportation of space exploration purposes (FAA, 2016).

For sake of clarity, in order to verify the data achieved in this phase of the work, a known example has been proposed, trying to verify whether the results of the roadmapping activity are compliant with the strategical plans proposed at that time in the selected example. In particular, IXV has been considered as example, freezing the time and the technological development to the pre-IXV mission era (i.e. 2006). IXV, initiated in the Future Launchers Preparatory Programme (FLPP) (Chavagnac, 2006), has performed in-flight experimentation of atmospheric re-entry the 11th of February 2015. In particular, IXV main objectives were the demonstration of some atmospheric re-entry capabilities, but also the development of these capabilities in the European context (Tumino, 2016), enabling future plans in several space fields such as reusable launchers stages, return from orbital infrastructures or planetary return missions.

Behind this European success, there are years of studies and demos. It has to be said that, reviewing IXV history (Cresto Aleina, 2017b), originally both ARD and X-38 technological advancements were contributing to the development of IXV technologies still at the beginning of 90's. In particular, considering X-38, some technologies related to the TPS were already at TRL 6 in 2000, but these achievements were lost for IXV project when the US has left the consortium. This has created a considerable time of delay in IXV project and the actual IXV study start can be considered around 2006.

Looking at other IXV technologies, it has to be said that in late 2012, the IXV's subsonic parachute system was tested in Arizona (USA) (Bennett, 2012)and water impact tests were conducted near Rome (Italy) (Iafrati, 2012). In 2013, probably the more important test was performed: an IXV test vehicle was dropped from an altitude of 3 km in Sardinia (Italy) with the purpose of validating the water-landing system, including the subsonic parachute, flotation balloons and beacon deployment. After the drop-test, the test vehicle was retrieved for further analysis, considering also that a small anomaly was encountered during the inflation of the balloons. A year later, the recovery ship Nos Aries conducted a training exercise involving a single IXV test article off the coast of Tuscany. Considering these studies and tests, even if the launch was originally scheduled for 2013, in 2014 a test campaign confirms IXV flight readiness and the launch.

4.2. TRIS Application: Preliminary Activities

First, the Research Study Objective is defined (Cresto Aleina, 2017a):

> "*To support the study of a transportation system able to transfer a payload in hyper-velocity in space or in an atmosphere, from ground to space and/or return. A Technology Roadmap will be defined to describe the elements and the processes related to the design and procurement of a SoS able to perform the requested mission safely.*"

At the same time, Stakeholder Analysis has been performed, taking into account the Research Study Objective. Examples of stakeholders according to the categorization proposed by (Larson, 2000) are:

- *Sponsors*: ESA (in this particular project);
- *Operators*: Ground stations, Space Agencies, Space and Aeronautical industries, the National Agency for Civil Aviation (or Ente Nazionale per l'Aviazione Civile, ENAC), each single Air Traffic Management systems (ATM), airlines companies, military aviation institutions;
- *End-users*: scientific community, universities and research centers;

- *Customers*: Space Agencies, airlines companies, military aviation institutions, research centers, governments.

Considering these stakeholders, a reference database has been chosen: HyDAT (Hypersonic DATabase) (Cresto Aleina, 2017a). HyDAT has been created to assist roadmapping and design processes for hypersonic systems. On the contrary, every criterion defined for ESA Space Exploration Technology Roadmaps and HERACLES case study, remains valid (see paragraph 2.2).

These first steps are fundamental to derive the Reference Mission Scenario (Figure 67), MCs design solutions and BBs design solutions. The Reference Mission Scenario is the envelope of every strategic Mission Phases, connecting the Earth surface and a hypothetical target (i.e. Earth orbit or celestial body vicinity) and it is split into three different phase types (i.e. launch/take-off, operative/cruise and re-entry/landing phase). In particular, it considers different strategic target environments around Earth according to (Jakhu, 2011): inner atmosphere (between Earth surface and about 30 km of altitude), outer atmosphere (between about 30 and 100 km of altitude), inner space (between about 100 km and an operative orbit, e.g. GEO) and outer space (over an operative orbit).

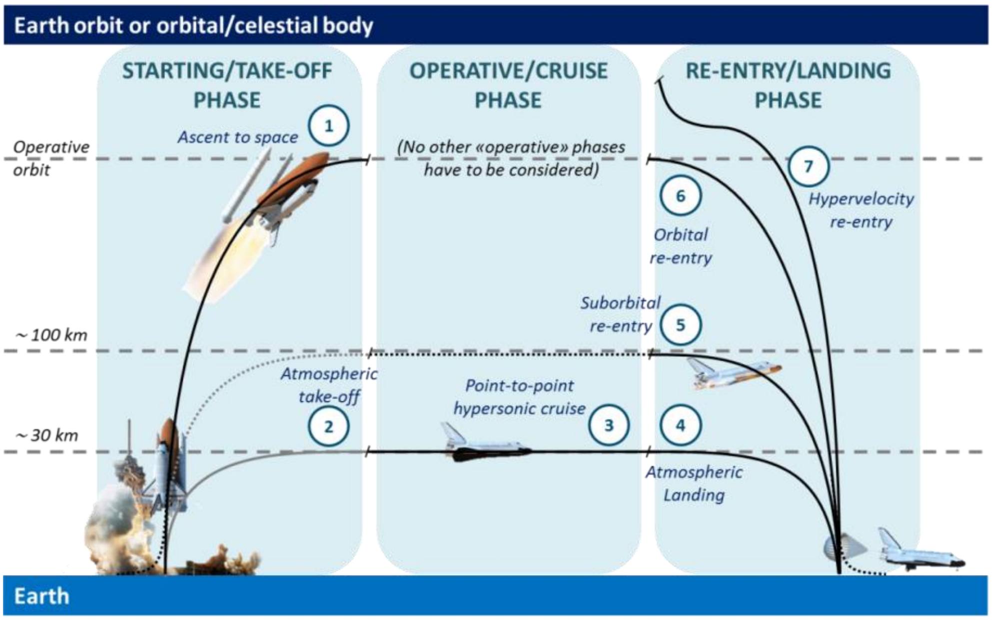


Figure 67: Reference Mission Scenario.

An additional target environment has to be added to consider every technological maturation activity that takes place in laboratory (e.g. Earth surface). In this way, it is possible to define every Mission Phases neglecting operative phases (i.e. focusing on trans-atmospheric/hypersonic phases).

According to this study stakeholders (i.e. looking at past, present and foreseen trans-atmospheric/hypersonic flights) it is possible to define the MCs design solutions. In particular possibilities for the number of stages (i.e. Single Stage To Orbit (SSTO), Two Stages To Orbit (TSTO) and 3 stages to orbit) and for take-off and landing (i.e. vertical take-off, horizontal take-off, vertical landing and horizontal landing). Similarly, it is possible to define BBs design solutions specifying the possibilities for take-off and landing (i.e. vertical take-off, horizontal take-off, harrier-like controlled vertical landing, tail-sitting controlled vertical landing, un-controlled vertical landing, horizontal landing, air-launched and air-dropped landing), the types of mission (i.e. human and robotic mission) and the types of BBs (i.e. reusable, partially reusable and expendable).

4.3. TRIS Application: Roadmap Development

Thanks to the preliminary activities, all the data are available to start a roadmapping process, following the method proposed in the previous chapters (see chapter 2 and 3 for details), i.e. TRIS.

4.3.1. Roadmap Elements Definition and Characterization Process

According to preliminary activities results it is possible to perform a Functional Analysis to define OCs categories, BBs categories, TAs and Technology Subjects as described in (Cresto Aleina, 2017d) (Figure 68).

Starting from the first level of functions defined in Figure 68 (i.e. *launch and take-off, cruise, landing, servicing* and *support* functions), OCs can be defined through trade space elements (see (NASA, 2010) for a different example). Trade-space elements have been identified as shown in (Cresto Aleina, 2017d) to incorporate all feasible alternatives regarding mission features possibilities and strategic performance trends. Analysing each high level function separately, two ways to define OCs are proposed. Indeed, the only constraint in the OCs definition is including only one performance for OC to be similar to a requirement. For example, is possible to define an OCs C_1as the combination of different the N Mission Features (mf) considered as different variables and a single Performance Type (pt):

$$C_1 = \bigcup_{i=1}^{N} mf_i + pt \cong Requirement \tag{4.1}$$

For example, Figure 69 shows the trade-space define through (4.1) for launch and take-off functions. As a result, 32 OCs are listed only for this OCs category (e.g. "*High capacity human flight with prepared launch for horizontal take-off*").

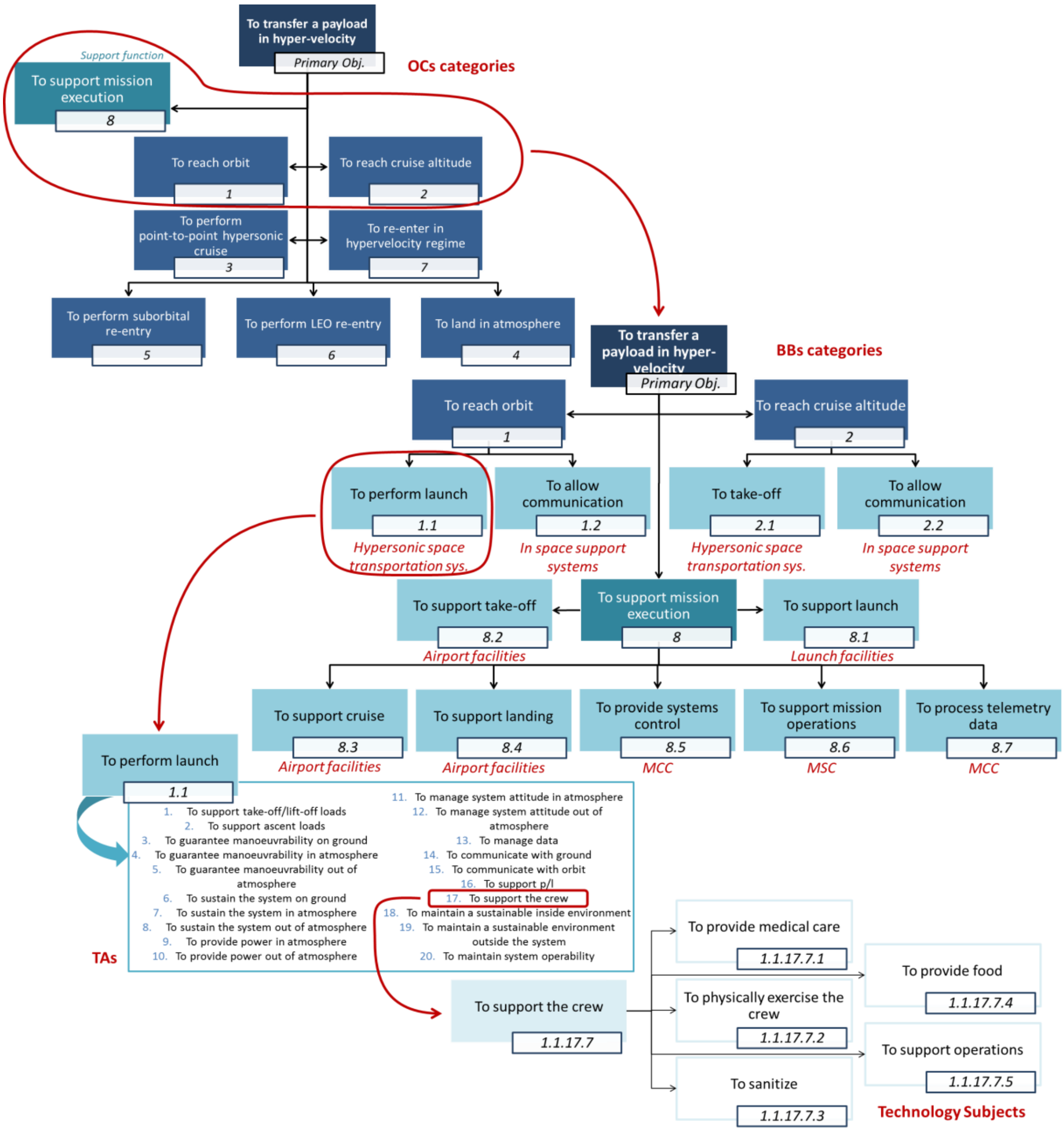


Figure 68: Functional Tree example.

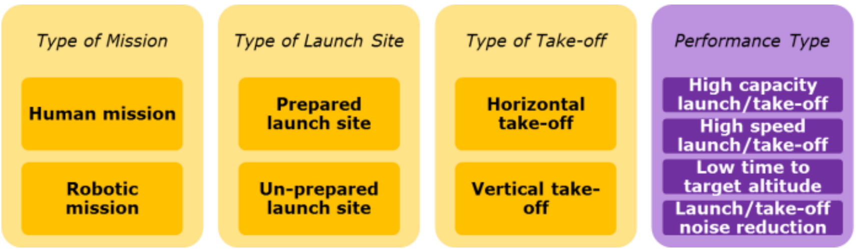


Figure 69: Trade-space elements related to launch and take-off functions with (4.1).

A second method can be combining only one mf with one pt:

$$C_2 = mf + pt \cong Requirement \qquad (4.2)$$

This trade-space is shown in Figure 70 again for launch and take-off functions, achieving 24 OCs only for this OCs category (e.g. "*High capacity launch/take-off in a human mission"*).

Figure 70: Trade-space elements related to launch and take-off functions with (4.2).

For simplicity, trade spaces for the other OCs categories are reported only for (4.2) and are shown in Figure 71 (defining 12 OCs), Figure 72 (defining 48 OCs through (4.1) and 36 OCs through (4.2)), Figure 73 (defining 4 OCs) and Figure 74 (defining 6 OCs). It has to be said that only Figure 72 can be applicable for both methods having more than one Mission Feature variable. The choice between the first and the second methods will be performed based on OCs impact on design definition.

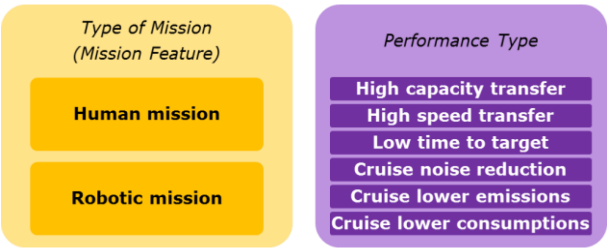


Figure 71: Trade-space elements related to transfer functions to be used with (4.2).

Figure 72: Trade-space elements related to landing functions to be used with (4.2).

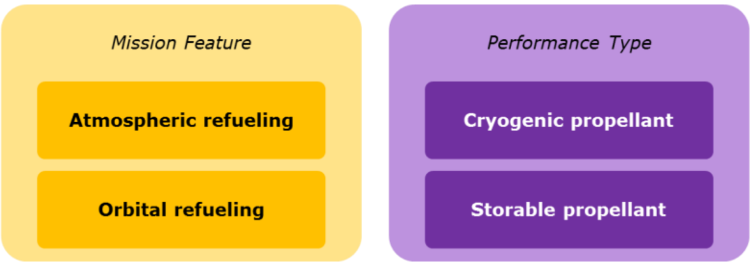


Figure 73: Trade-space elements related to servicing (i.e. refuelling) functions with (4.2).

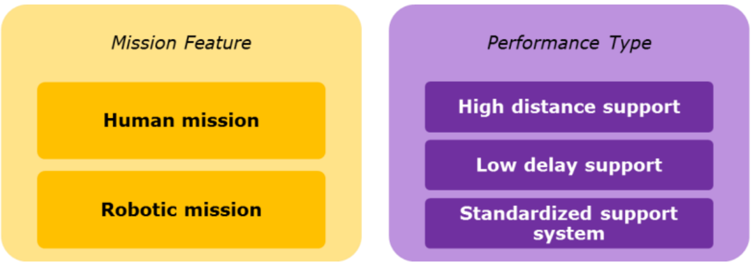


Figure 74: Trade-space elements related to mission support functions with (4.2).

A similar analysis has defined the final BBs, starting from a certain number of BBs categories: *Hypersonic space transportation systems, On-orbit support systems, In-flight refuelling systems, Launch facilities, Airport facilities, Mission Control Centers (MCC)* and *Mission Support Centers (MSC)*. For example, through Figure 75 the hypersonic space transportation system has been decomposed into 18 lower level BBs. The same process has been applied to all BBs, which have been subdivided into the following lower level BBs:

1. *On-orbit support systems*: communication satellite/network, small satellite (single or in a network), balloon, Unmanned Aerial System (UAS), aircraft;
2. *In-flight refuelling systems*: space tug, UAS, aircraft;

3. *Launch facilities*: ground prepared spaceport, sea prepared spaceport, un-prepared launch site (with no support), un-prepared launch site with mobile support facility;
4. *Airport facilities*: ground prepared airport, floating prepared airport, un-prepared runway (with no support), un-prepared runway with mobile support facility;
5. *MCCs*: fixed facility, mobile facility;
6. *MSCs*: fixed facility, mobile facility.

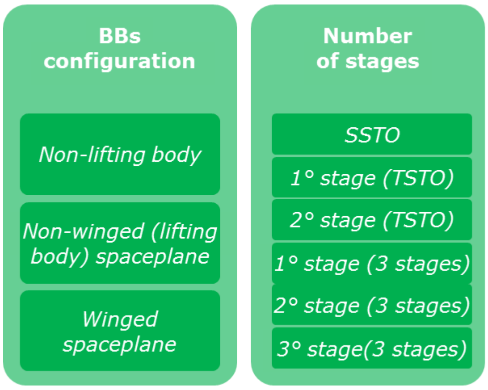
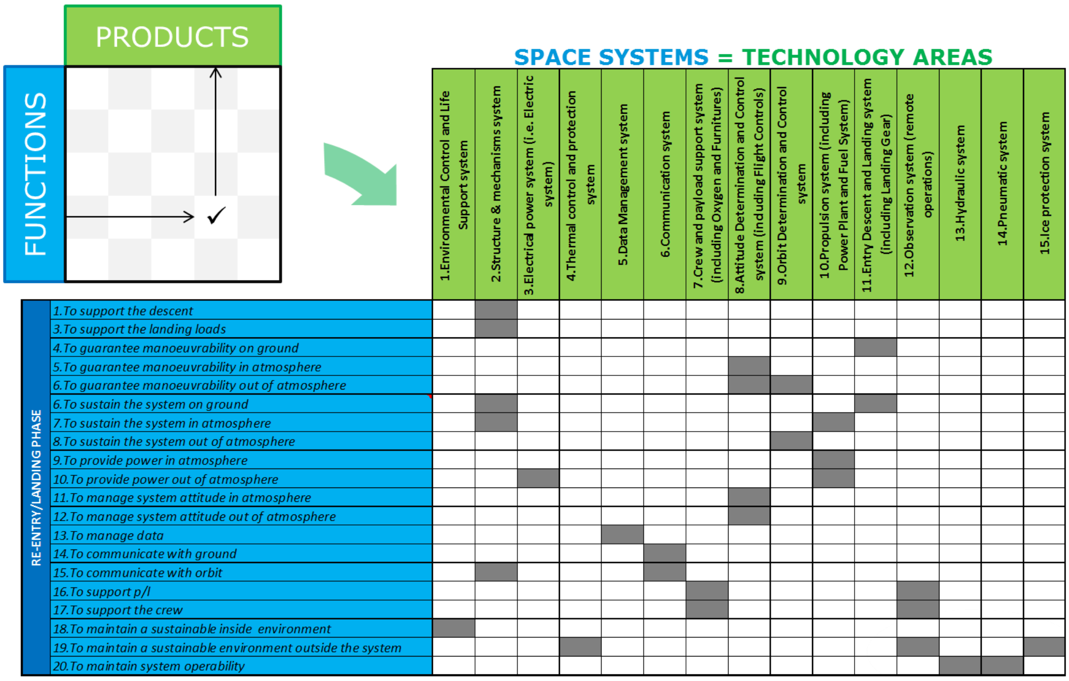


Figure 75: Simplified representation of the trade space for lower level BBs generation for hypersonic space transportation system.

Proceeding with the Functional Analysis, TAs are defined looking at products able to perform the defined functions and are then linked to these functions through Functions/Product matrixes (Figure 76). in particular, the following TAs are defined as explained in (Viola, 2016): *Environmental Control and Life Support system*, *Structure & mechanisms system*, *Electrical power system*, *Thermal control and protection system*, *Data Management system*, *Communication system*, *Crew and payload support system*, *Attitude Determination and Control system*, *Orbit Determination and control system*, *Propulsion system*, *EDL system*, *Observation system*, *Hydraulic system*, *Pneumatic system* and *Ice protection system*. Typical space and aeronautical sub-systems are included. For example, the aeronautical "*Avionic Sub-system*" is divided into different TAs looking at the devices that compose it, such as displays and warning systems that are contained in the "*Data Management system*".



		1.Environmental Control and Life Support system	2.Structure & mechanisms system	3.Electrical power system (i.e. Electric system)	4.Thermal control and protection system	5.Data Management system	6.Communication system	7.Crew and payload support system (including Oxygen and Furnitures)	8.Attitude Determination and Control system (including Flight Controls)	9.Orbit Determination and Control system	10.Propulsion system (including Power Plant and Fuel System)	11.Entry Descent and Landing system (including Landing Gear)	12.Observation system (remote operations)	13.Hydraulic system	14.Pneumatic system	15.Ice protection system
RE-ENTRY/LANDING PHASE	1.To support the descent		▨													
	3.To support the landing loads		▨													
	4.To guarantee manoeuvrability on ground											▨				
	5.To guarantee manoeuvrability in atmosphere								▨							
	6.To guarantee manoeuvrability out of atmosphere								▨	▨						
	6.To sustain the system on ground		▨									▨				
	7.To sustain the system in atmosphere		▨								▨					
	8.To sustain the system out of atmosphere									▨						
	9.To provide power in atmosphere										▨					
	10.To provide power out of atmosphere			▨							▨					
	11.To manage system attitude in atmosphere								▨							
	12.To manage system attitude out of atmosphere								▨							
	13.To manage data					▨										
	14.To communicate with ground						▨									
	15.To communicate with orbit		▨				▨									
	16.To support p/l							▨					▨			
	17.To support the crew							▨					▨			
	18.To maintain a sustainable inside environment	▨														
	19.To maintain a sustainable environment outside the system				▨								▨			▨
	20.To maintain system operability													▨	▨	

Figure 76: Example of Functions/Products Matrix.

Through function and Products Tree these TAs (i.e. systems) can be divided into Technology Subjects (i.e. equipment), such as the "*Atmosphere Control*" or "*Water and Gas Delivery*" for "*Environmental Control and Life Support*" TA. Finally, 260 possible technology subjects are identified (Cresto Aleina, 2017d).

To derive the technologies, a sizing feature for each Technology Subject can be defined. For example, considering "*Landing Bags*" Technology Subject ("*EDL system*" TA), sizing features are "Mass" (kg), "Volume (stowed)" (m^3), "Volume (deployed)" (m^3) and "Power" (kW). Between them, the "Volume (stowed)" is the sizing feature, considering launch phase constraints. Proceeding as explained in paragraph 3.3.1 is possible to define the following technologies, leaving the definition of the three levels to HyDAT: Landing Bags with low stowed volume, Landing Bags with medium stowed volume and Landing Bags with high stowed volume.

Both operational and demonstrative MCs stem out from the composition of different legs of the Reference Mission Scenario, as highlighted in Figure 77. It has to be remembered that while operational MCs have to start from Earth surface and end at list in another strategic target environment, demonstrative MCs can be partial operational MCs, that needs the support of BBs different from the one present in the *Hypersonic space transportation systems* category. Finally, a certain number of technology maturation activities have to be foreseen (e.g. "*laboratory components/breadboard validation*" on ground to reach TRL 4). To define this list every consideration done in paragraph 3.3.1 remains valid.

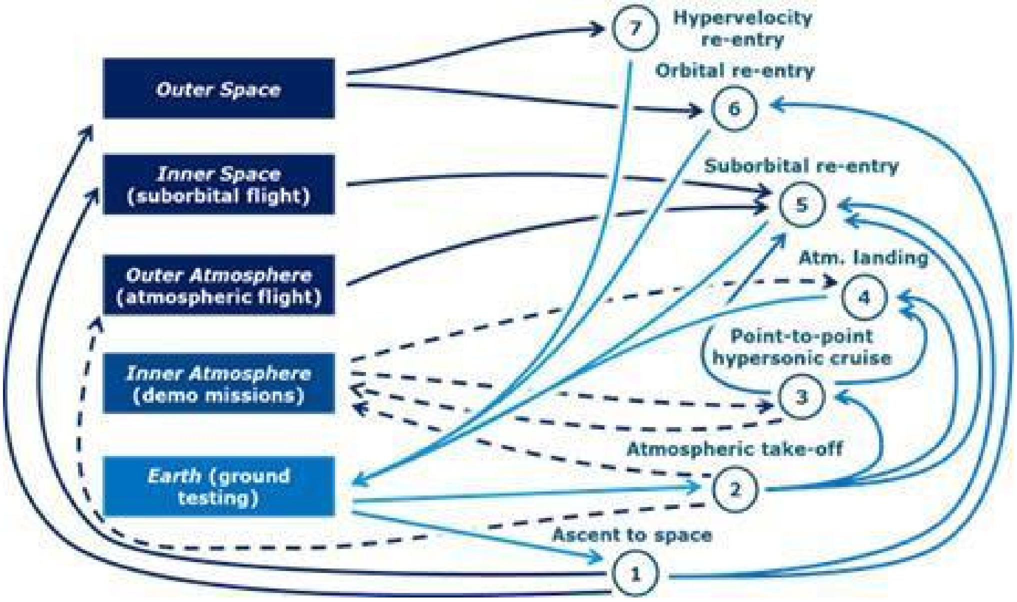
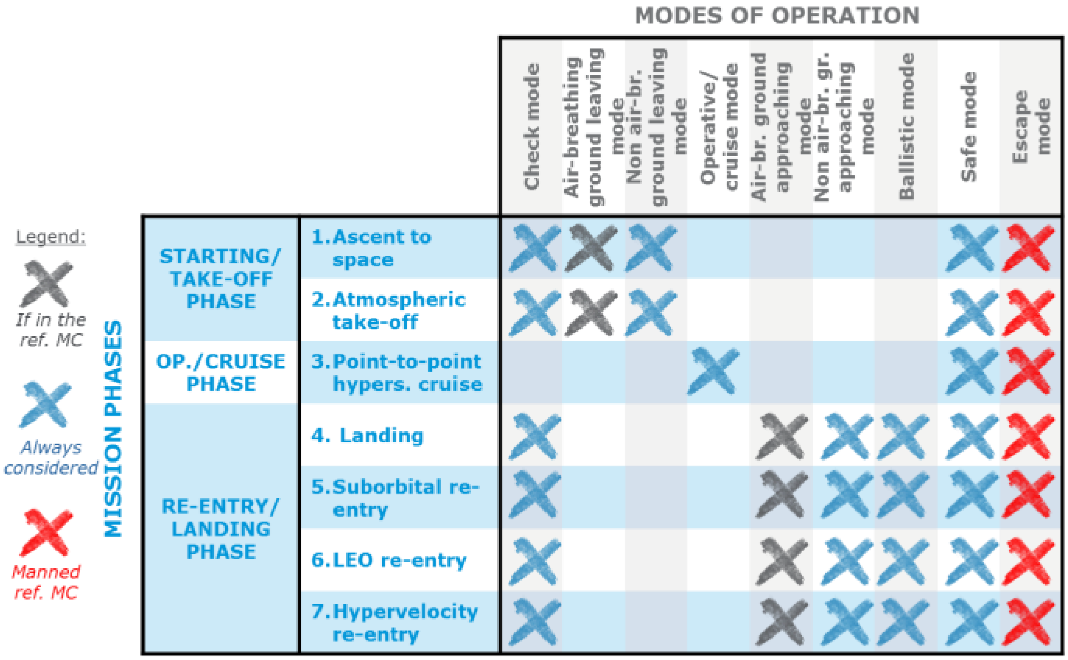


Figure 77: Legs of the Mission Reference Scenario for operational MCs generation. *Dotted lines are for demonstrative purposes only.*

In the context of the Research Study Objective, some approved mission exist (e.g. *Space Ship II*), but it is not significant in proposing new scenarios in the roadmap. Under approval MCs, on the contrary, have to be listed, e.g. the *Sänger TSTO*, that performs a point-to-point hypersonic cruise. These two last categories of MCs have to be derived from HyDAT looking at the defined stakeholders. Excluding these MCs for simplicity, 46 MCs are listed considering only the Mission Phases combinations (i.e. 16 operational missions, 24 demonstrative missions and 6 technologies maturation activities).

Further data are needed to characterize every possible operational and demonstrative MC. First, modes of operations have been defined and linked to the Technology Subjects and the Mission Phases (Figure 78) according to (Viola, 2016). Modes of Operations considered are the following: *Check mode*, *Air-breathing ground leaving mode*, *Non air-breathing ground leaving mode*, *Operative/cruise mode*, *Escape mode*, *Non air-breathing ground approaching mode*, *Air-breathing ground approaching mode*, *Ballistic mode* and *Safe mode*.



		Check mode	Air-breathing ground leaving mode	Non air-br. ground leaving mode	Operative/ cruise mode	Air-br. ground approaching mode	Non air-br. gr. approaching mode	Ballistic mode	Safe mode	Escape mode
STARTING/ TAKE-OFF PHASE	1. Ascent to space	X	X	X					X	X
	2. Atmospheric take-off	X	X	X					X	X
OP./CRUISE PHASE	3. Point-to-point hypers. cruise				X				X	X
RE-ENTRY/ LANDING PHASE	4. Landing	X				X	X	X	X	X
	5. Suborbital re-entry	X				X	X	X	X	X
	6. LEO re-entry	X				X	X	X	X	X
	7. Hypervelocity re-entry	X				X	X	X	X	X

Figure 78: Mission Phases vs Modes of Operations.

Looking at the high number of elements listed, in order to verify TRIS application, a simplified example has to be proposed. Based on the TPS state of the art at the pre-IXV mission, TRIS will be applied to verify the possibility to define IXV case study. Considering present literature (Tumino, 2008), IXV design is started in 2006 with the major objectives of developing European capabilities and technological know-how for a re-entry mission. Considering IXV starting year, the technological scenario at 2006 (i.e. pre-IXV state-of-the art) is considered as input.

According to (Fusaro, 2017), TAs involved were the TPS and Hot Structures, GNC, Cold Structures and Mechanisms, Avionics, Flight Control System and Descent and Recovery System. In order to propose an example, only the critical areas will be considered, i.e. TPS and Hot Structures that was the major challenge (Buffenoir, 2016). In particular, Table 15 reports the critical technologies for IXV (Tumino, 2016; Buffenoir, 2016) that will be analysed with TRIS. It has to be noticed that all the technologies studied in 2006 to be potentially selected in IXV are listed. Modes of Operations selected for each technology are Check mode, Non air-breathing. Ground approach, Mode, Ballistic/Glide Mode and Safe Mode. CaC has been divided between the different TRL transits according to Figure 57.

Final TRL to be reached is considered at 8, as the potential TRL reached by IXV according to literature according to 2006 assumptions (Tumino, 2008) and the final budget is 25 Mio€ for the only TPS (Viola, 2016).

Table 15: IXV example data (Behrens, 2004).
Flexible External Insulation (FEI), Surface Protected Flexible Insulation (SPFI), metallic and ceramic TPS are included.

ID- Technology	**TRL**		**CaC (Mio€)**	**Time to final TRL (years)**	**$T_{ultimate}$ (°C)**	**Hot Structure**	**Past projects**
	Start (2006)	*End (2015)*					
1 - FEI with low ultimate temperature	7	8	1.5	2.2	800	Base	SHEFEX, HOPPER, ASTRA, HERMES, TETRA, X-38
2 - FEI with medium ultimate temperature	7	8	1.5	2.2	1200	Leeward Assembly	SHEFEX, HOPPER, ASTRA, HERMES, TETRA, X-38
3 - FEI with high ultimate temperature	6	8	1.6	7.2	1300	Lateral Assembly	SHEFEX, HOPPER, ASTRA, HERMES, TETRA, X-38
4 - SPFI with high ultimate temperature	5	8	4.4	9.1	1400	Windward Assembly	EXPERT, HOPPER, SHEFEX, PRE-X. X-38
5 - Metallic (TiAl) TPS with medium ult. temp.	4	8	13.8	9.3	900	Windward Assembly	ASTRA, HOPPER
6 - Metallic (ODS) TPS with high ult. temp.	4	8	13.8	9.3	1200	Nose, Body Flap Ass.	EXPERT, ASTRA, HOPPER
7 - Ceramic TPS with high ultimate temperature	5	8	17.21	9.1	2000	Nose, Body Flap Assembly	EXPERT, HOPPER, FESTIP, SHEFEX, SHyFE, LEA, FOTON

4.3.2. Applicability Analysis

At this point it is possible to derive the applicability maps (Cresto Aleina, 2017d). For simplicity in Figure 79, Figure 80 and Figure 81 are shown three of the four maps for the IXV example at the second iteration (i.e. after the elements impacts on design definition). Indeed, the applicability map between MCs and technologies does not show any incompatibility, according to the Modes of Operations analysis. In Figure 82 are shown the main results achieved.

It has to be noticed that, thanks to Figure 81, every operative and demo MCs has to be considered three times to test separately technologies with ID #1, #2 and #3 being of the same Technology Subject. This division is exploited by technologies with ID #5 and #6 for the same reason. This is only a proposal to a TRIS user that will be able to avoid this division.

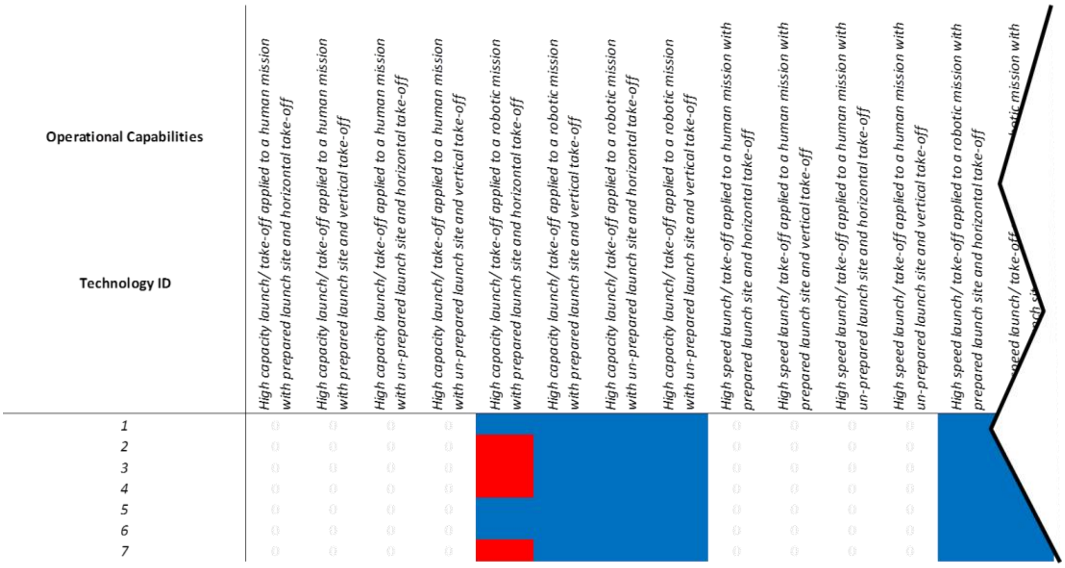


Figure 79: Applicability map between technologies and OCs.

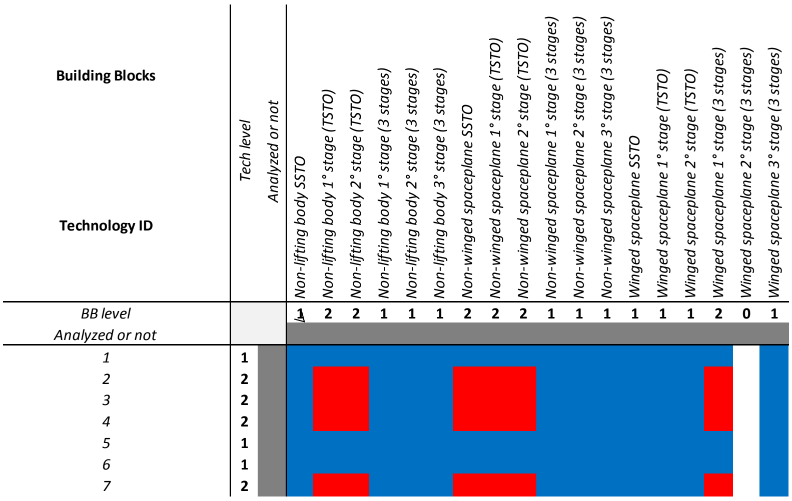


Figure 80: Applicability map between technologies and BBs.

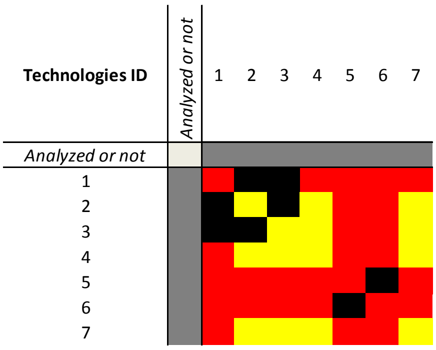
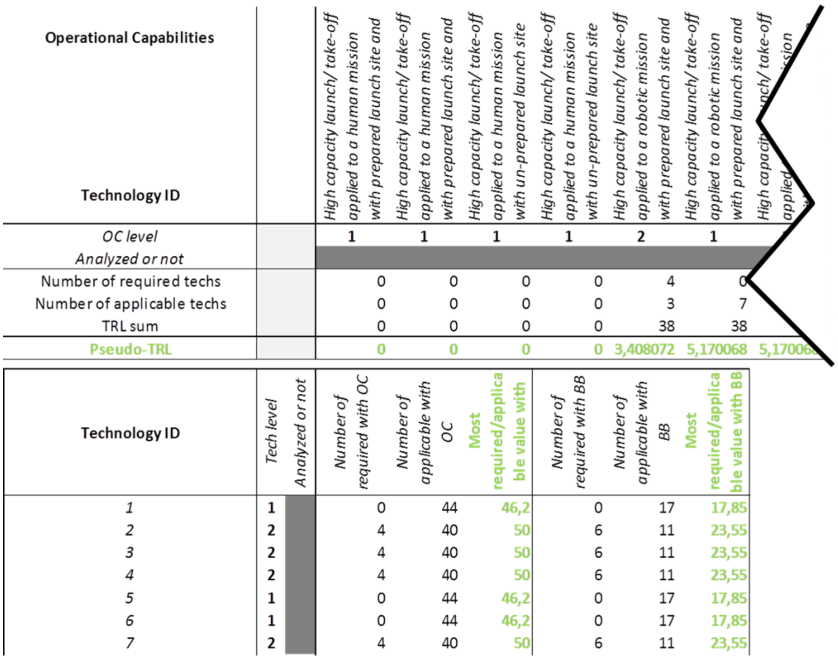


Figure 81: Applicability map between technologies (compatibility analysis).



Operational Capabilities / Technology ID		High capacity launch/ take-off applied to a human mission with prepared launch site and	High capacity launch/ take-off applied to a human mission with prepared launch site and	High capacity launch/ take-off applied to a human mission with un-prepared launch site	High capacity launch/ take-off applied to a human mission with un-prepared launch site	High capacity launch/ take-off applied to a robotic mission with prepared launch site and	High capacity launch/ take-off applied to a robotic mission with prepared launch site and	High capaci unch/ take-off applied ission
OC level		1	1	1	1	2	1	
Analyzed or not								
Number of required techs		0	0	0	0	4	0	
Number of applicable techs		0	0	0	0	3	7	
TRL sum		0	0	0	0	38	38	
Pseudo-TRL		**0**	**0**	**0**	**0**	**3,408072**	**5,170068**	**5,17006**

Technology ID	*Tech level*	*Analyzed or not*	*Number of required with OC*	*Number of applicable with OC*	***Most required/applicable value with***	*Number of required with BB*	*Number of applicable with BB*	***Most required/applicable value with BB***
1	1		0	44	46,2	0	17	17,85
2	2		4	40	50	6	11	23,55
3	2		4	40	50	6	11	23,55
4	2		4	40	50	6	11	23,55
5	1		0	44	46,2	0	17	17,85
6	1		0	44	46,2	0	17	17,85
7	2		4	40	50	6	11	23,55

Figure 82: Pseudo-TRL and the most applicable/required over OCs and BBs.

4.3.3. Sensitivity Analysis

As explained in the previous chapter, starting from a nominal set of labels (i.e. required level at 2 and applicable one at 1) and looking at about the 50% of differences distributions (Figure 83), a required weight of 2 and an applicable one of 1.05 are proposed.

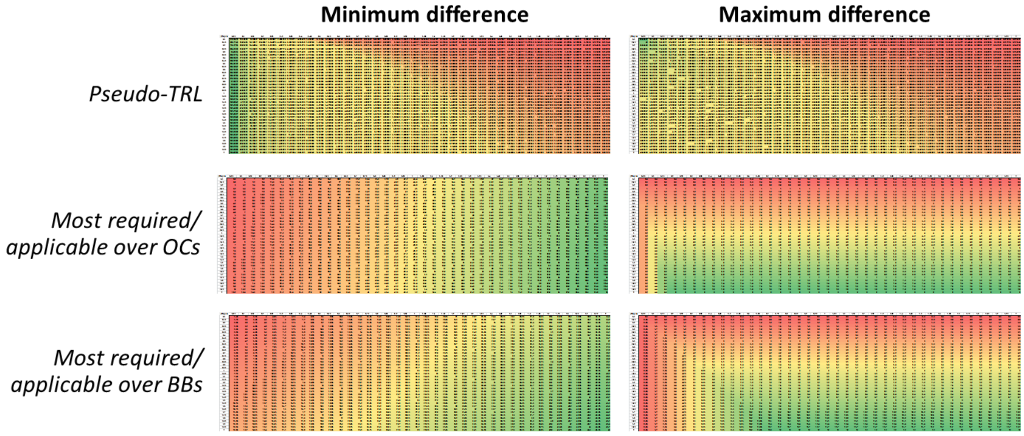


Figure 83: Sensitivity analysis tables.

In each tables columns are the options for the applicable weight and the rows are options for their differences with the required weight. Note that green areas are the higher values and red areas are the lower ones.

4.3.4. Prioritization Studies

Based on the previous phases' results, the main purpose of this phase is to rank technologies and MCs and to define impacts on design for technologies, BBs and OCs, in order to suggest and weight preferable paths to be followed in the roadmap definition.

4.3.4.1. Roadmap elements impact on design analysis

For the technologies impact on design analysis, the following criteria have been selected (Cresto Aleina, 2017d):

1. *Higher applicability in BBs* (by stakeholders with economic needs);
2. *Higher applicability in OCs* (by stakeholders with general public needs),
3. *Lower TRL* (by stakeholders with scientific need);
4. *Higher TRL* (by stakeholders with technological needs);
5. *High AD2* (by stakeholders with technological needs).

While 4 criteria have been defined through the analysis of IXV mission objectives, criterion #4 is there proposed to analyse the influence of TRL over the case study. The only filter specified is on criteria #3 and #4, where a filter at TRL 5 (included) for both is considered.

Choosing to evaluate FoMs on the first 4 technologies thanks to a sensitivity analysis (Figure 84), the optimal solution is reached considering as able to create enabling technologies criteria #1, #2, #4 and #5 and as able to create enhancing technologies criterion #3. For this combination, the TRL cost-effectiveness is at 0.67, the average costs increase is at 0.02 and the total probability of failure is at 0.86 (e.g. a total value of 1.24). The results are reported in Table 16.

Table 16: Technologies priority and prioritization for the IXV example data.

Technology ID	**Priority**
1	**Enabling**
2	**Enhancing**
3	**Enhancing**
4	**Enhancing**
5	**Enabling**
6	**Enabling**
7	**Enhancing**

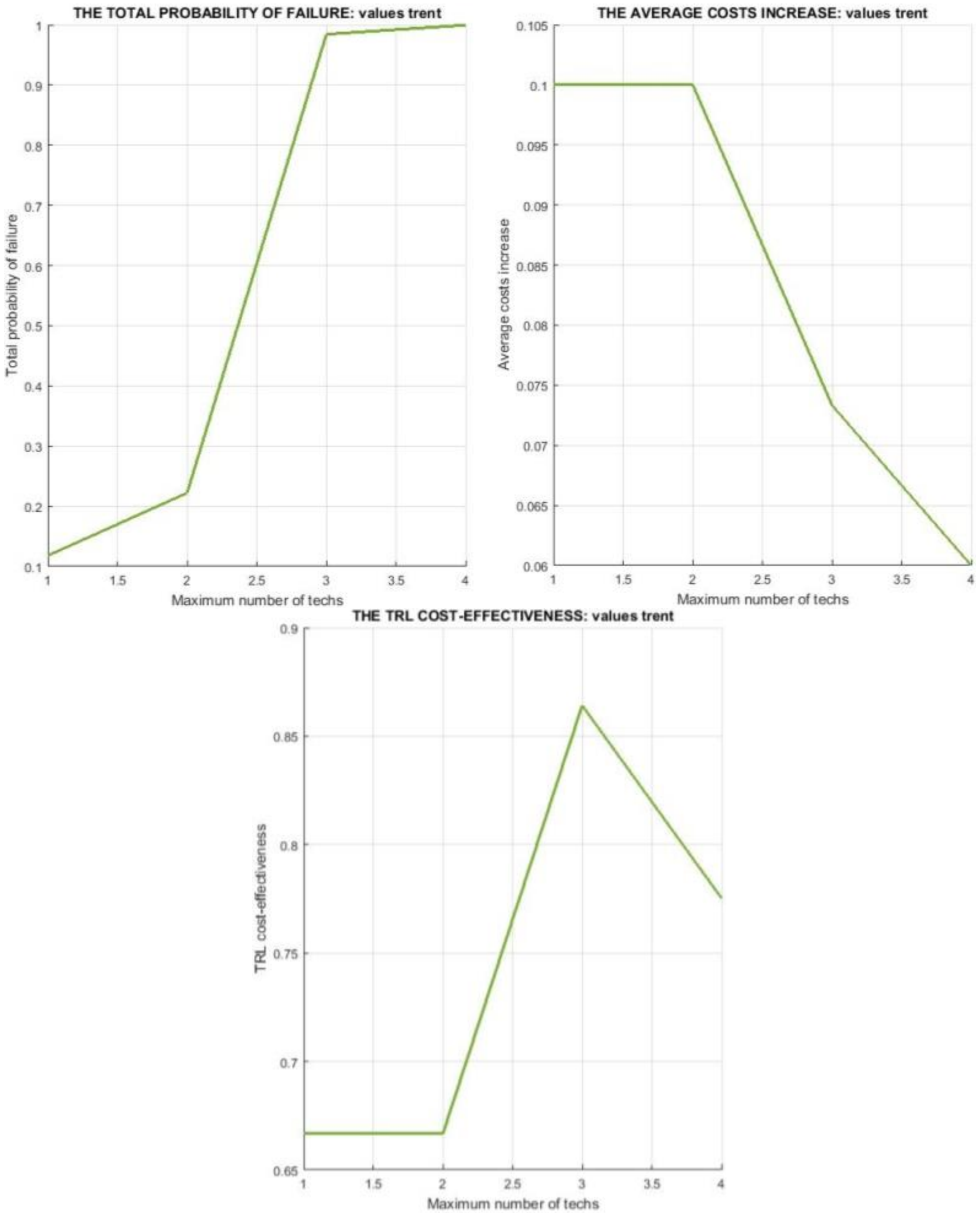


Figure 84: Sensitivity analysis results.
Different colours means different criteria combinations.

Then it is possible to apply the method proposed in paragraph 3.3.4.1 to define OCs and BBs impacts on design. To obtain the values for the two criteria (i.e. objectives), the following considerations have been considered:

1. Objective 1 (“*To have solutions with an higher competitiveness*”) is considered at 0 for alternatives already tried, 0.5 for alternatives considered in studies and at 1 for alternatives difficult to achieve;
2. Objective 2 (“*To have less risky solutions*”) is considered at 0 for alternatives combination of high risk, 0.5 for alternatives combination of acceptable risk and at 1 for combination of negligible risk.

In particular, in Table 17 and Figure 85 are shown the results achieved for the OCs related to servicing functions and in Table 18 and Figure 86 the results achieved on the BBs list. Note that, the hypothetical optimum point is imposed to have at least a competitive mission feature or performance type and to have a risky level equal to the minor one.

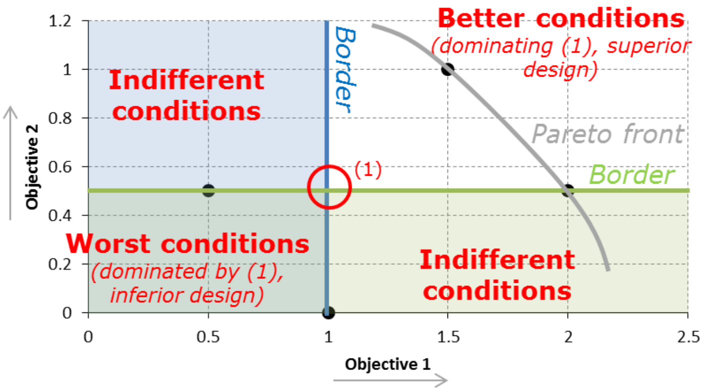


Figure 85: Results for the impact on design analysis criteria on refuelling OCs.
(1) marks the hypothetical optimum point.

Table 17: Example of results for the impact on design analysis criteria on refuelling OCs.

OCs	Obj 1	Obj 2
Atmospheric refuelling with cryogenic propellant	1	0
Atmospheric refuelling with storable propellant	0.5	0.5
Orbital refuelling with cryogenic propellant	2	0.5
Orbital refuelling with storable propellant	1.5	1

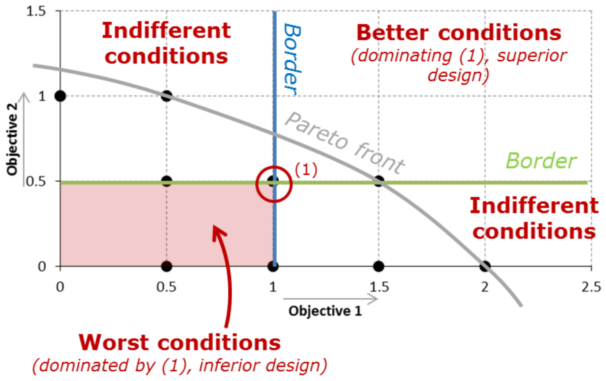


Figure 86: Results for the impact on design analysis criteria on BBs.
(1) marks the hypothetical optimum point.

Table 18: Results for the impact on design analysis criteria on BBs.

BBs	**Obj 1**	**Obj 2**
Non-lifting body SSTO	1	0.5
Non-lifting body 1° stage (TSTO)	0.5	1
Non-lifting body 2° stage (TSTO)	0.5	1
Non-lifting body 1° stage (3 stages)	0	1
Non-lifting body 2° stage (3 stages)	0	1
Non-lifting body 3° stage (3 stages)	0	1
Non-winged spaceplane SSTO	2	0
Non-winged spaceplane 1° stage (TSTO)	1.5	0.5
Non-winged spaceplane 2° stage (TSTO)	1.5	0.5
Non-winged spaceplane 1° stage (3 stages)	1	0.5
Non-winged spaceplane 2° stage (3 stages)	1	0.5
Non-winged spaceplane 3° stage (3 stages)	1	0.5
Winged spaceplane SSTO	1.5	0
Winged spaceplane 1° stage (TSTO)	1	0
Winged spaceplane 2° stage (TSTO)	1	0.5
Winged spaceplane 1° stage (3 stages)	0.5	1
Winged spaceplane 2° stage (3 stages)	0.5	0
Winged spaceplane 3° stage (3 stages)	0.5	0.5

In addition, the same method can be applied on both the OCS obtained through (4.1) and (4.2) (Figure 87).Comparing the results achieved through (4.1) and (4.2), both in terms of OCs lists and OCs impacts on design it is possible to demonstrate that (4.1) gives the bets results. This is true not only for the higher number of OCs defined, but also because, even if (4.2) has a higher modularity of the results, (4.1) is able to reduce the number of OCs required to describe a single mission. Finally, according to the number of variables involved, 4 OCs obtained through (4.1) are able to fully describe an OCs obtained through (4.2), while the contrary is possible only with 3 OCs. Looking at the entire list of OCs obtained through the two formulas and excluding the not important OCs, it can be seen that only the OCs obtained through (4.1) are still able to fully describe the one obtained through (4.2) (Cresto Aleina, 2017d).

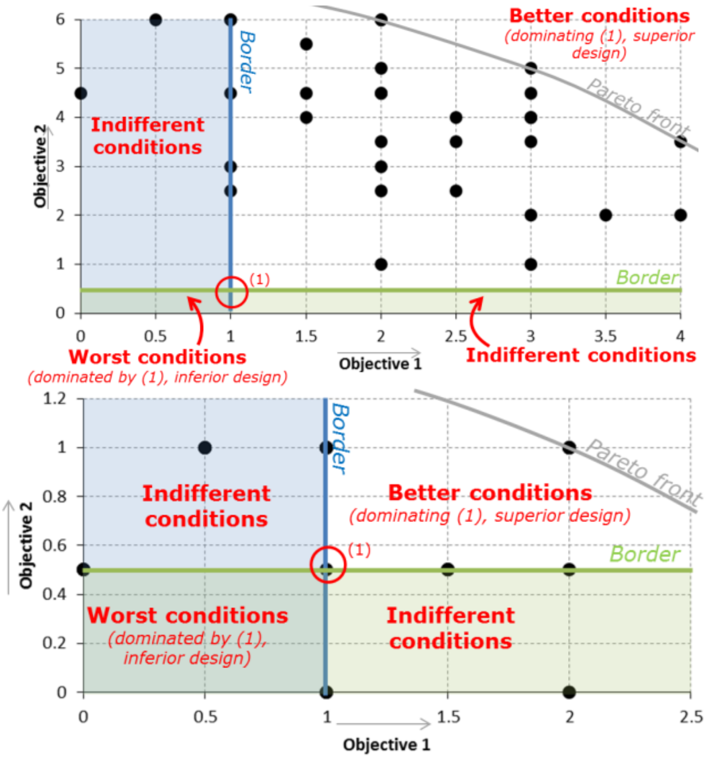


Figure 87: Results of the trade-off performed over the OCs definition processes with (4.1) on the left and with (4.2) on the right.

As a result, 9 BBs enabling, 8 BBs enhancing and 1 BB not important are defined. Looking only at the OCs defined through (4.1), 14 OCs enabling and 88 OCs enhancing are selected.

4.3.4.2. Technologies ranking

For the technologies ranking are used the same 5 criteria applied in paragraph 4.3.4.1, with the same stakeholders requiring them. Applying the method explained in paragraph 3.3.4.2 and choosing to evaluate FoMs on the first 3 technologies thanks to a sensitivity analysis (Figure 88), the optimal solution is reached considering the criteria in this particular order: #1, #5, #2 and #3. It has to be noticed that, being the purpose of the criterion #4 only the analysis of the influence of TRL over the case study, this criterion has been excluded from the final results. For this combination, the TRL cost-effectiveness is at 0.28, the average costs increase is at 0.02 and the total probability of failure is at 0.9996 (e.g. a total value of 0.00066). The results are shown in Table 16.

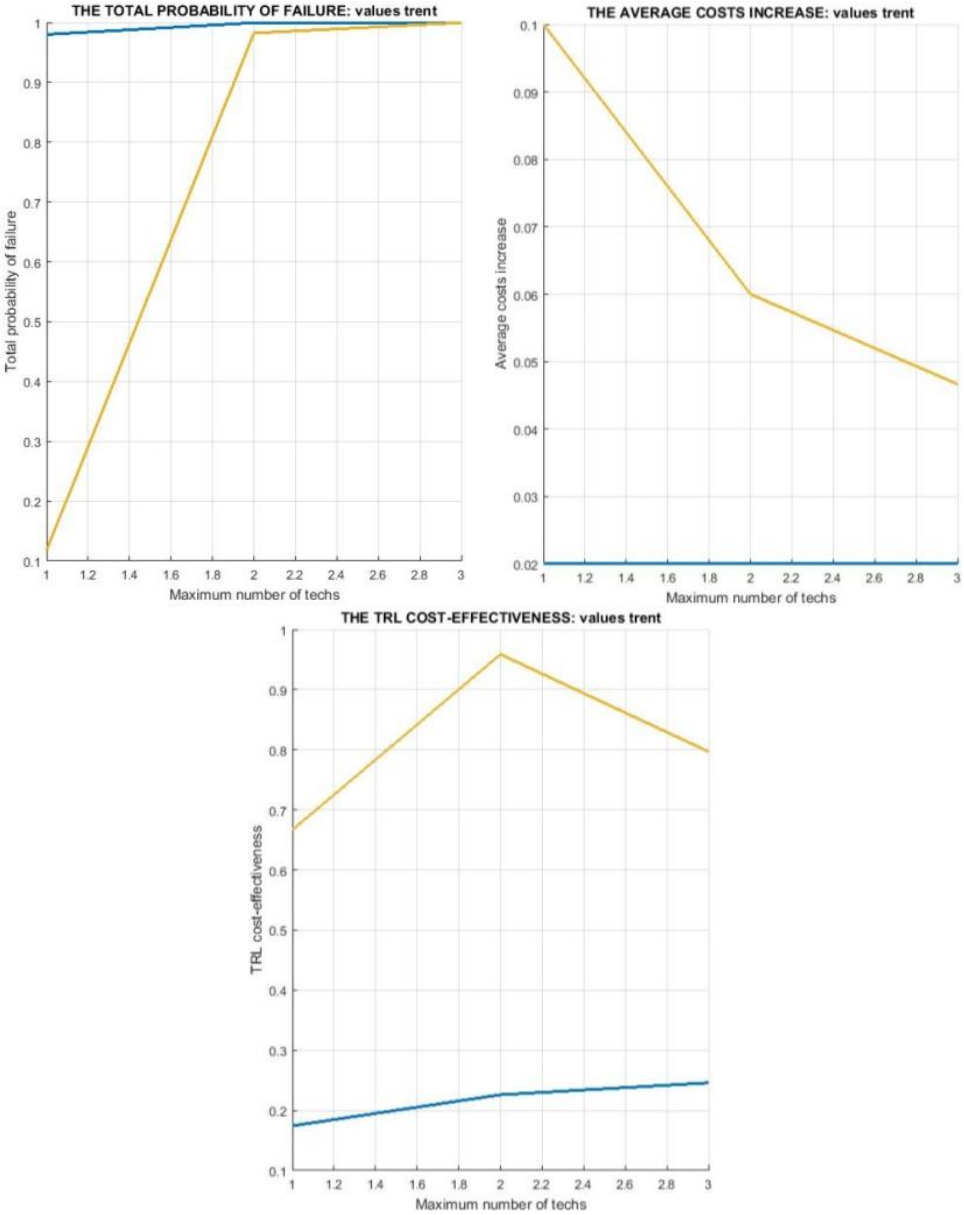


Figure 88: Sensitivity analysis results.
Different colours means different criteria combinations.

Table 19: Technologies priority and prioritization for the IXV example data.

Technology ID	Prioritization level
1	6
2	4
3	3
4	1
5	6
6	7
7	2

4.3.4.3. MCs ranking

The prioritization of MCs has been performed applying these criteria and in this order, with the main purpose of simplifying the planning definition: *by required budget* in ascending order, *by target environment distance from ground* in ascending order, *by number of Modes of Operations* in descending order, *by number of applicable/required technologies* in descending order and *by minimum TRL required* in ascending order.

It has to be noticed that finding data about the required budget is difficult, especially for a mission to be proposed. For this reason, a weight has been applied to estimate at least a reciprocal trend for this value and between the different MCs (Figure 89). Indeed every MCs has been characterized by number of legs involved (i.e. MCs complexity) and if it has been already tried or not (i.e. MC level of innovation, giving a weight of 0 if tried, 0.5 if studies are present and 1 if none of the previous options). The required budget weight is the sum between these two values. Both the results with and without a value for the required budget weight will be shown.

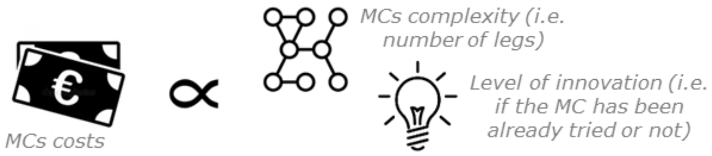


Figure 89: Required budget weight main influences.

4.3.5. Planning Definition

Starting from the data derived until now and considering the data present in HyDAT, it is possible to propose a planning. It has to be said that not all the data required are present in HyDAT and some of them, being significant for the analysis, have to be estimated (e.g. TRL transit costs and duration). Figure 90 shows the relationship between US DoD lifecycle phases, technology maturity (i.e. TRL), TRL transit costs and duration and it has been derived applying the TRL transit duration proposed in Figure 59 to a timeframe of 10 years as already explained and the CaC division proposed in Figure 57.

Distributing the available budget between the different technologies is possible to find out that only 4 technologies can be selected to reach TRL 8 (i.e. technologies with ID #2, #3, #4 and #7) with a final budget of about 24.74 Mio €. Their TRL increase path includes the following MCs types (Figure 92):

1. A technology maturation activity to reach TRL 6 to be performed on ground in a laboratory that can be considered as a relevant environment and this for each technology taken separately;
2. A demonstrative mission to reach TRL 7 (i.e. an hypersonic point-to-point mission in outer atmosphere for the first case and a suborbital re-entry mission in inner space for the second case);
3. An operative mission to reach TRL 8 with the same mission phases composition of the previous demo.

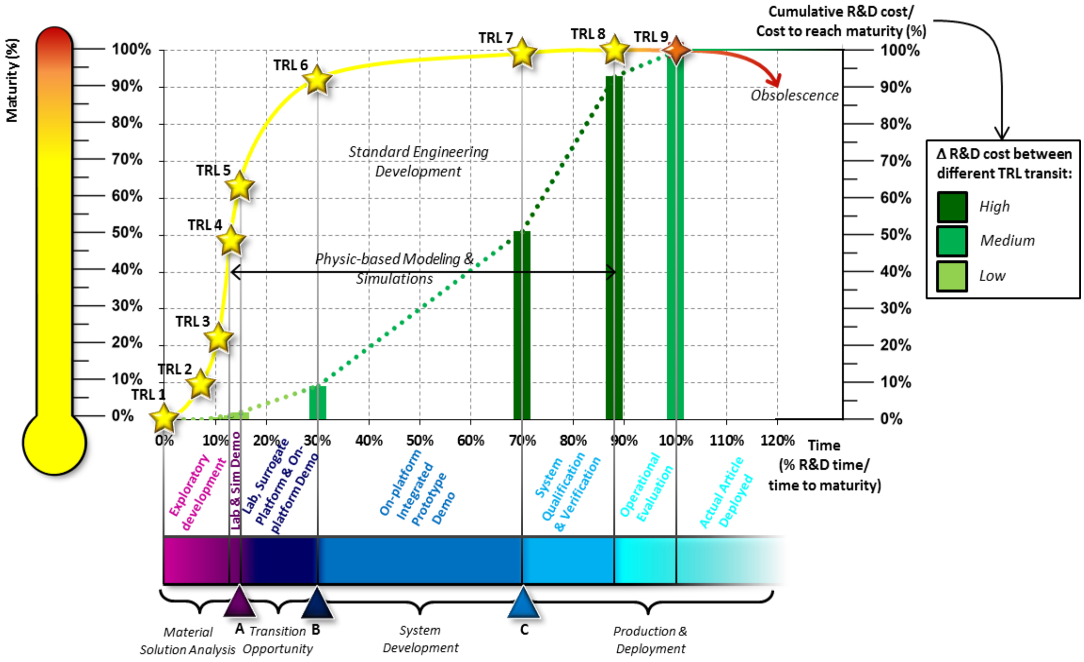


Figure 90: Project phases and generalized expectation for the TRL and CaC evolution.

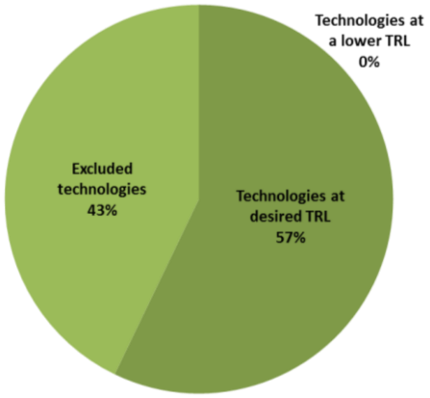


Figure 91: Summary of the technologies status at the end of the nominal roadmap.

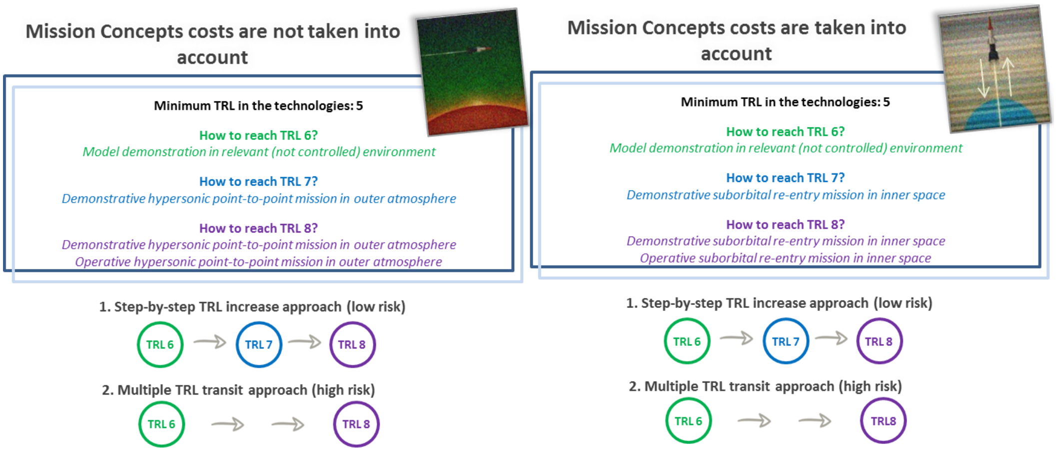
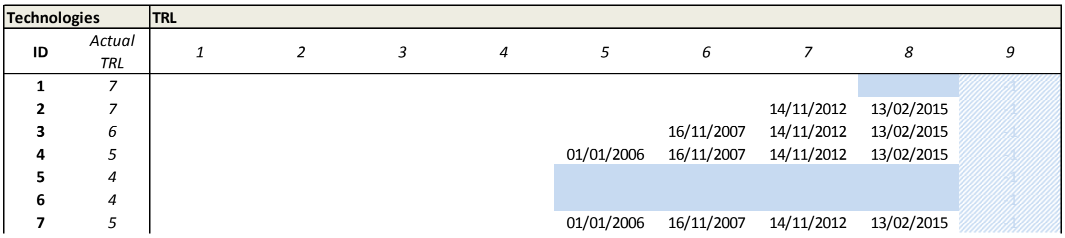


Figure 92: MCs choice with and without MCs required budget estimation.

While a single operative mission can be supposed, for the demo mission the possible incompatibility between the technology with ID #2 and the technology with ID #3 has still to be studied and for this reason two separate MCs are there supposed. It has to be noticed that, in both cases being the same MC able to perform both the TRL transit between 6 and 7 and the one between 7 and 8, a single mission can be proposed to perform the TRL transit between 6 and 8. This choice is left to the user, having a higher risk. Finally, looking at the TRL transit durations is possible to propose a schedule (Figure 93), to be performed between the 1st of January 2006 and the 13th of February 2015.



Technologies		TRL								
ID	Actual TRL	1	2	3	4	5	6	7	8	9
1	7									-1
2	7							14/11/2012	13/02/2015	-1
3	6						16/11/2007	14/11/2012	13/02/2015	-1
4	5					01/01/2006	16/11/2007	14/11/2012	13/02/2015	-1
5	4									-1
6	4									-1
7	5					01/01/2006	16/11/2007	14/11/2012	13/02/2015	-1

Figure 93: Schedule definition.

4.3.6. Results Evaluation

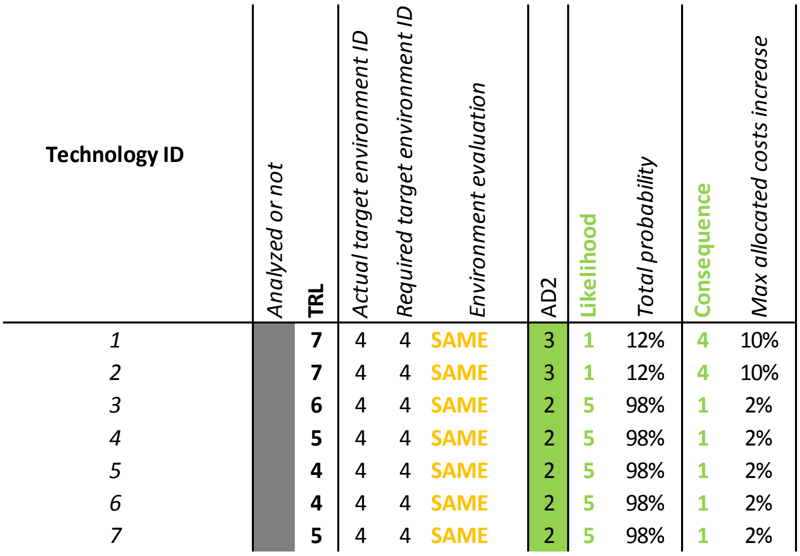
Table 20 shows the main results obtained for the TRL to reach sensitivity analysis. Looking at the CaC division suggested between the different TRL transits, it could be seen that the transit between TRL 6 and 7 is expensive if compared to the others. For this reason, imposing a TRL to reach lower than 6 or 7 allow involving more technologies in the final roadmap (i.e. technologies with ID #5 and #6 that reach respectively TRL 6 and 5). In applying a lower TRL to reach, the main strategy applied is to enhance the highest number of technologies, while in applying an higher TRL to reach (as in the present case), the main purpose is to obtain a flight model able to be tested and operated.

Table 20: TRL sensitivity analysis for the IXV example.

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%

Looking at out of nominal situations, the delays are potentially between 0 and 22 years with a statistic average of 11 years and with higher frequency between 9 and 13 years. Reviewing IXV history (Cresto Aleina, 2017b), IXV delay is of about 8 years considering that originally both ARD and X-38 advancements were contributing to the development of IXV technologies. In particular, considering X-38, some technologies related to the TPS were already at TRL 6 in 2000, but these achievements were lost for IXV project when the US has left the consortium. A delay of 8 years is at the 30th percentile. Finally, (Cresto Aleina, 2017b) suggest a way to estimate possible over-costs starting from experts' opinion.

Additionally, a draft risk analysis has been performed following the method proposed in 3.3.6.1 (Figure 94). Thanks to this analysis is possible to estimate a total allocated cost increase of about 0.6 Mio€.



Technology ID	*Analyzed or not*	**TRL**	*Actual target environment ID*	*Required target environment ID*	*Environment evaluation*	AD2	**Likelihood**	*Total probability*	**Consequence**	*Max allocated costs increase*
1	▨	**7**	4	4	SAME	3	1	12%	4	10%
2	▨	**7**	4	4	SAME	3	1	12%	4	10%
3	▨	**6**	4	4	SAME	2	5	98%	1	2%
4	▨	**5**	4	4	SAME	2	5	98%	1	2%
5	▨	**4**	4	4	SAME	2	5	98%	1	2%
6	▨	**4**	4	4	SAME	2	5	98%	1	2%
7	▨	**5**	4	4	SAME	2	5	98%	1	2%

Figure 94: AD2 analysis for the IXV example.

Comparing the IXV project with the nominal roadmap, TRIS is able to identify IXV TPS technologies, a similar schedule (IXV mission has been successfully completed on the 11th of February) and a similar final budget. It has to be noticed that in the case with MCs budget supposed, TRIS is able to select a MC similar to the IXV one (i.e. a suborbital re-entry mission in inner space). In the case without an estimation of MCs budgets, the different MC type selected (i.e. a hypersonic point-to-point mission in outer atmosphere) is because the proposed MC has not only more operative modes and technologies applicable than the IXV one, but is also placed in a lower target environment (i.e. outer atmosphere and not inner space). Indeed, for the technologies involved a similar MC can be the best and safer choice for a test or a demo (without considering additional technologies tested with IXV).

Finally, it has to be said that the number of mission for the TPS is higher than in the real case (TPS technologies were tested only in the IXV experiment). This is mainly due to the need of a step-by-step approach for the TRL increase path definition, but, in case stakeholders can afford in terms of resources and risks to perform more TRL transit in one MC, this problem is not present.

4.4. TRIS Application: Roadmap Visualization and Update

Once the technology roadmap definition process is completed, all data need to be updated and (at least periodically) reviewed. HyDAT, if linked to a tool based on TRIS, will play an important role in the update of the roadmap elements after the roadmap definition and in the continuous update of the roadmap after this first iteration.

Figure 95 and Figure 96 show the nominal roadmap achieved for the case in which a step-by-step approach is proposed for the TRL increase path (i.e. one MC performs one TRL transit) and the case in which one MC performs more TRL transit.

4.5. Highlights

- ✓ TRIS has been applied to derive a technology roadmap for hypersonic and re-entry transportation systems in a European scenario;
- ✓ Starting from the definition of a roadmap for hypersonic space transportation and re-entry systems, an example concerning the TPS state of the art at the pre-IXV mission era is considered for verification purposes;
- ✓ IXV design is started in 2006 with the major objectives of developing European capabilities and technological know-how for a re-entry mission: in the example, the TPS situation at 2006 is considered as starting scenario;
- ✓ Comparing the IXV project with the nominal roadmap, TRIS is able to identify IXV TPS technologies, a similar schedule (IXV mission has been successfully completed on the 11th of February), a similar final budget and MCs similar to the IXV one (i.e. a suborbital re-entry mission in inner space).

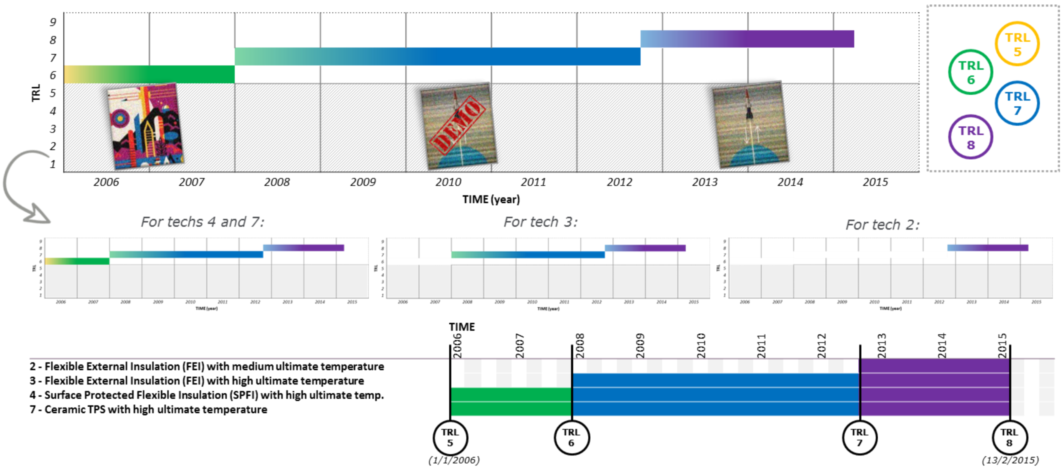


Figure 95: Example of graphical view of the roadmap for TPS related technologies development for the IXV mission, in case of a step-by-step approach for the TRL increase path.

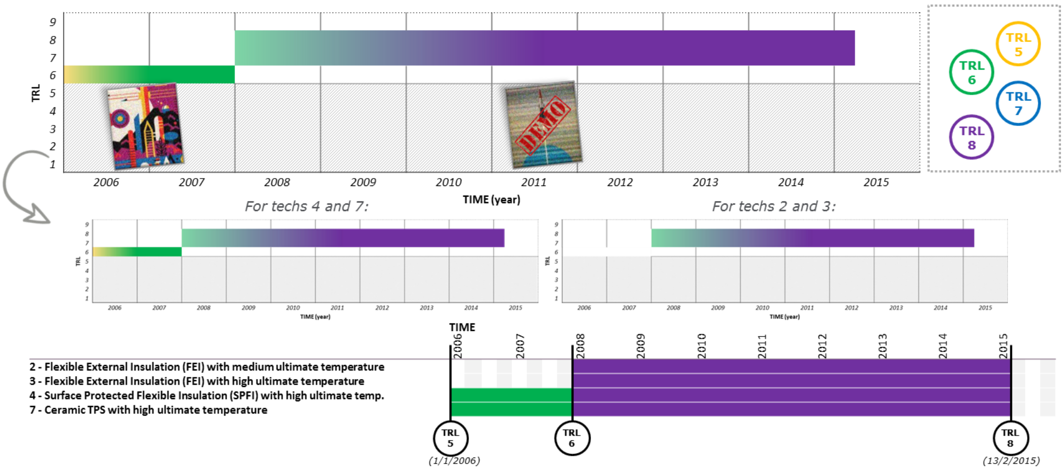


Figure 96: Example of graphical view of the roadmap for TPS related technologies development for the IXV mission, in case multiple TRL transit with one MC is allowed.

Chapter 5

TRIS Application: Reusable Space Tug in Earth Vicinity

The objective of the space tug presented in this chapter is to improve the national space operability in terms of access to space by providing a transportation system capable to transfer satellites platforms from low orbits, where they are released by launcher, to higher operational orbits and back, if needed. This objective may need a particular un-manned pre-deployed system, the Space Tug. This system has to be correctly designed in order to fulfil all the needs and the objectives of STRONG project. Considering STRONG space tug (i.e. a generic robotic, reusable space tug with an electric propulsive system able to operate between LEO and GEO, Figure 97) and expanding it to the European market for simplicity, a roadmap will be generated exploiting TRIS. Differently from the precious case, no example exists for comparison, but the results can be compared with the existing roadmaps (such as (ESA, 2015b)).

Figure 97: STRONG space tug depiction (Cresto Aleina, 2016d).

5.1. Context and roadmap scenario

The final main case study presented considers the enhancement of all those technologies related to a reusable space tug in Earth vicinity. In addition, this system is strategic for space exploration initiatives, considering that, in recent years the space is becoming crowded for an increased interest in space exploration and a space tug, for its capabilities, can be a solution to reduce the number of orbital systems (ISECG, 2018). The increase number of orbital systems is obviously related to the increased interest from the private sector in space applications, while historically the access to space was mainly a government prerogative. This interest can be seen in the amount of financial resources employed in the space sector: for example, in 2014 the overall amount of financial resources was of about 330 billion dollars and this value is grown from the previous year of about 9% (American Space Foundation, 2015) (Figure 98).

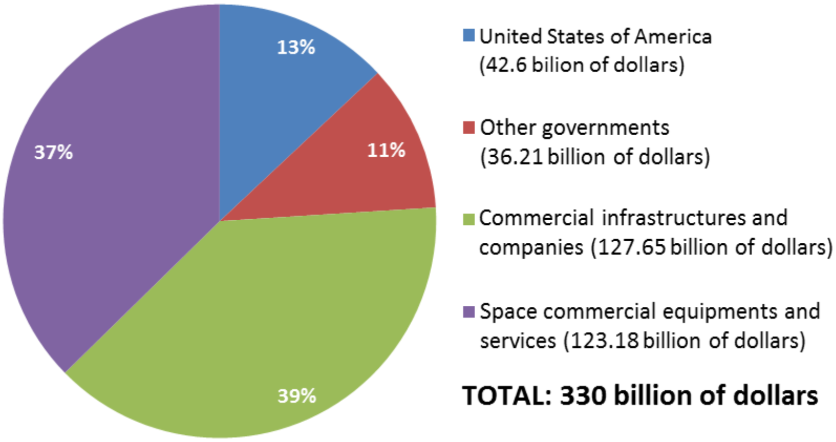


Figure 98: Space sector global available financial resources distribution in 2014 (American Space Foundation, 2015).

A space tug vehicle is a particular space service system aimed at performing rendezvous and docking manoeuvre in space with a generic object, at evaluating its asset and status and at stabilizing it in its current or in a new orbit. In addition, it is usual for a space tug to be at least partially reusable (Jefferies, 2015). The space tug is not a recent concept (Galabova, 2003), but it is currently a strategic technological objective in the aerospace field for its capability of increasing space missions' effectiveness, in terms of cost reduction and resources saving (ESA, 2015a). Indeed, space tugs have a wide range of applications (Figure 99) and, between them, the most promising examples are the satellite servicing (Viscio, 2013c) and the support to space exploration.

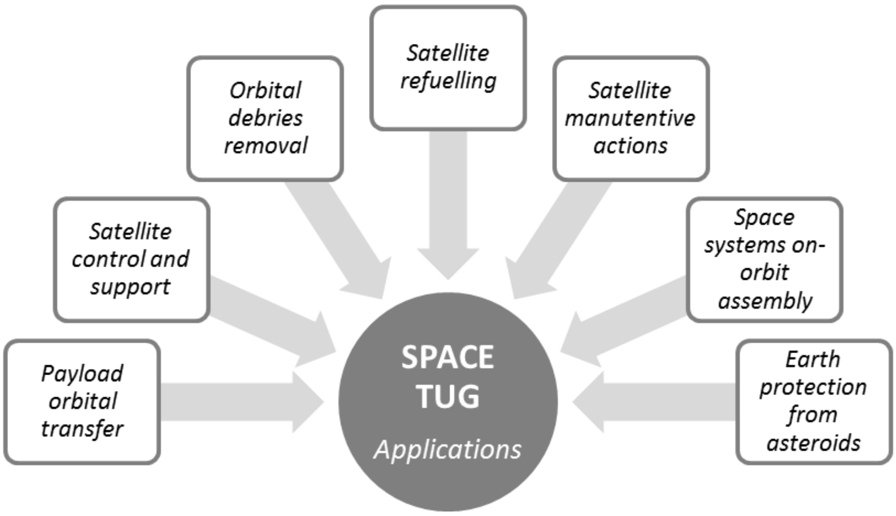


Figure 99: Possible missions based on a Space Tug.

Considering the satellite-servicing missions, examples are payloads retrieving (Galabova, 2003), maintainability actions (Richards, 2005), refuelling (Manzo, 2007) and cargo resupply service (Sevastiyanov, 2006). In particular, the use of tugs for orbital transfer manoeuvers or for the on orbit refuelling allows simplifications in satellite design (i.e. in the propulsion system) reducing its mass and volume (Harrison, 1971). In addition, considering the combined use of small launchers and space tugs, it is possible to reach LEO with a higher payload and then move it to its operative orbit not through dedicated on-board systems or through launcher stages, but through on-orbit service systems such as space tugs. On the contrary, considering space tug support to space exploration missions, an example is the on orbit assembly of larger spacecraft or planetary outposts. Indeed, Aerojet Rocketdyne has demonstrated capabilities related to assembly and servicing of a cis-lunar deep space habitat, with significant costs reductions and logistics simplifications (DeMaster-Smith, 2013).

While the very first application of a space tug is for the transfer of interplanetary probes from LEO to escape orbits (Mason, 1972), different kinds of studies are present in literature. For example, in (Schweickart, 2003) is analysed a potential asteroid impact with Earth, proposing to attach a space tug to its surface to slowly push it away to its trajectory. A different application can involve small space systems, considering, for example, the use of small launcher combined to a Space Tug to employ CubeSats or other Small Satellites in interplanetary missions (Viscio, 2014b, 2013b). Finally, an example of currently designed space tug is the SHERPA system proposed by the Spaceflight Inc. (Andrews, 2012). SHERPA main capability will be to transfer small and secondary payloads to their operative orbits, supported by a SpaceX's Falcon 9 launch. In particular, this system is composed by a ring structure able to dock with payloads and by a VASIMR (Variable Specific Impulse Magnetoplasma Rocket), theoretically capable of carrying tons of payloads from LEO to Low Lunar Orbit (LLO) in few months.

In this context, a space tug design is also the main output of STRONG (Systems Technology and Research National Global Operations), sub-project of the project SAPERE (Space Advanced Project for Excellence in Research and Enterprise) (Cresto Aleina, 2015a). SAPERE is a cluster project born with the partnership of European space companies, universities and research institutes active in the space sector. SAPERE activities are divided between two sub-projects: STRONG and SAFE (Space Assets For Emergencies). While SAFE has the main purpose of identify and improve space services in the management of emergency on ground, SRONG main objective is to improve the Italian space operability in terms of access to space and to increase the national industrial capability to realize an unmanned reusable space tug dealing with electric propulsion. In addition, in STRONG a further scenario is considered, with the strategic aim of increasing the designed space tug capability in cooperating with international system. Indeed, the possibility to retrieve on Earth significant payload samples by means of an operative reusable vehicle, such as Space Rider vehicle (previously known as PRIDE, Programme for Reusable In-orbit Demonstrator for Europe), has to be analysed. STRONG space tug is an example of strategic system applied in a restricted scenario (i.e. the Italian industrial scenario). For these reasons, considering STRONG project reusable space tug as reference, an example of nominal roadmap will be generated exploiting TRIS, sizing the results according to the SoS architecture features and requirements.

Even if a context that is more confined than the case study explained in section 1.1, also considering the STRONG program architecture means considering a SoS. This context is confined if compared to the previous example, because it can be considered as contained in it. Indeed, not only it is composed by a certain number of individual systems able to cooperate between them, but it is also true that political, social and economic factors play an important role in this program. For example, considering STRONG project, the roadmapping approach has to deal with a certain number of constraints (Cresto Aleina, 2016d). First, the space tug has to be reusable and this feature is enhanced by a refuelling system. In addition, STRONG space tug is a robotic system that does not have the capability to transfer human beings and the only exception is the case in which it has to transfer a crew as a payload. Another important constraint is related to its inability of a safe re-entry: to re-enter payloads, Space Rider is foreseen. Another constraint related to STRONG project is the use of electrical propulsion to reduce the fuel consumption providing a better reliability and design simplicity than chemical systems (Cresto Aleina, 2017c), even if it offers longer transfer times. Finally, the possibility of multiple space tug assembly will be considered to enlarge STRONG project scenario.

5.2. TRIS Application: Preliminary Activities

The Research Study Objective has been defined looking at STRONG space tug mission statement (Cresto Aleina, 2016d) and including the European market:

> *"To improve the national space operability in terms of access to space by providing a transportation system capable to transfer satellites platforms between LEOs to operational orbits, relying on Italian and European space assets."*

Again in (Cresto Aleina, 2016d) the main stakeholders have been defined for the STRONG case study. Influent stakeholders if the European market is considered can be space agencies such as ESA and ASI (Agenzia Spaziale Italiana or Italian Space Agency) (e.g. political stakeholders) and industries with studies related to space tugs (i.e. technological stakeholders) such as Thales Alenia Space Italia (TASI) (Cresto Aleina, 2016d, 2016a). Additional stakeholders have to be related to the scenario in which the SoS architecture under analysis is placed (i.e. general public stakeholders). In particular, (Grover, 2008; NASA, 2010) will be used as reference. Considering the selected stakeholders and case study, a reference database has been chosen: TREx (Saccoccia, 2017).

According to (ESA, 2015a), ESA activities are aimed at enhancing technologies in critical and competitive areas (i.e. areas with many applications but low TRL), giving for example importance to electrical propulsion. Secondly, ESA aims at enhancing European market competitiveness in terms of both science and economic development, for example exploiting global cooperation. In addition, ASI activities according to (Battiston, 2016) are meant at promoting services and applications for the space economy, at enhancing the scientific and cultural advancement and at increasing the national international status. Similarly, according to (Messidoro, 2013), TASI main focus concerns the development of the key technologies and concepts to enable targets environments such as Mars. Industrially, it is strategic also the adaptation and standardization of space platforms and products with the aim of increasing their reusability. The same need for standardization can be found in strategies and priorities for stakeholders coming from society and market (Grover, 2008; NASA, 2010), with the aim of keeping costs competitive and enhancing international cooperation. Stakeholders' main strategic needs can be summarized in these criteria (Cresto Aleina, 2017c):

1. *To give high priority to lower TRL technologies*, focusing on the technologies with a TRL lower than 4 (ESA);
2. *To enhance BBs competitiveness*, i.e. BBs features first objective as explained in paragraph number 4.3.4.1 (ESA and ASI);
3. *To enhance BBs reusability*, weighting differently BBs' features according to their reusability such as refuelling operations or the docking with a passive target (TASI);
4. *To give high priority to lower CaC technologies* (society and market).

According (ESA, 2015a), usual target environments are Earth vicinity, Moon, and Mars surface and vicinity and the Mars Moons. Currently, space tug capabilities have to be demonstrated in GEO, with the aim of expanding their application to Moon vicinity (Gatti, 2012). For this reason, focusing on "Earth Vicinity" target, a list of sub-target of interest can includes: LEO, Medium Earth Orbit (MEO) and GEO (Cresto Aleina, 2017c). It has to be remembered that Earth Atmosphere and Laboratories have to be included for technological maturation purposes. In detail, considering STRONG scenario as reference (Figure 100), the reference mission starts with the launch of the space tug through VEGA (Vettore Europeo di Generazione Avanzata or Advanced Generation European Carrier Rocket) (Bott, 2014). Then the space tug remains in its parking orbit until the launch of a payload platform at a certain launch orbit. After RvD manoeuvres, the platform can be transferred to its final operational orbit. There the space tug releases the platform moving to a refuelling orbit or to its parking orbit. Finally, an additional scenario is considered, i.e. the retrieval to Earth of payloads interfacing with the pre-operational vehicle Space Rider (Figure 101).

Different options for refuelling are considered and compared in STRONG project including interfaces with standardized or international systems in the space scenario (Cresto Aleina, 2015d). In particular, five options have been analysed:

1. Full refuelling before each platform transfer with a dedicated platform;
2. Full refuelling before each platform transfer with propellant stored in VEGA last stage (i.e. AVUM, Attitude Vernier Upper Module);
3. Partial refuelling before each payload platform transfer with the platform and periodic full refuelling with a dedicated platform;
4. Full refuelling after each platform transfer with an orbital tank module at the parking orbit;
5. Full refuelling after each platform transfer with ISS, exploiting CO_2 tanks outside the ISS.

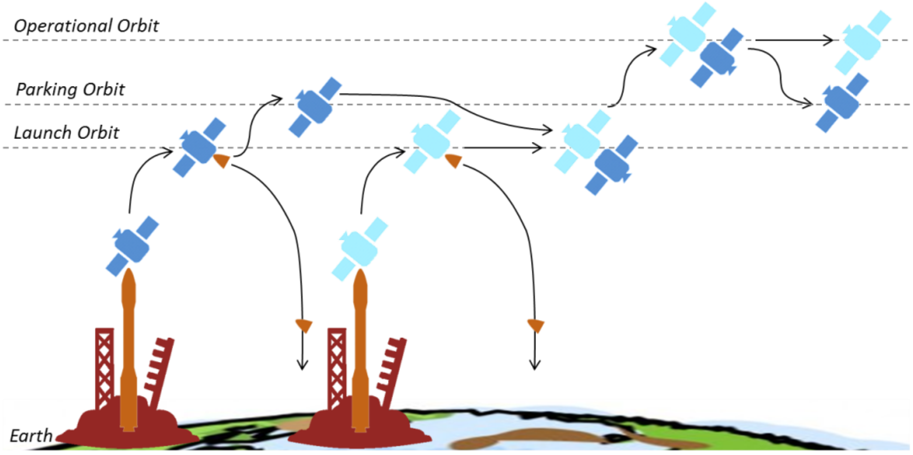


Figure 100: Nominal electric space tug MC.

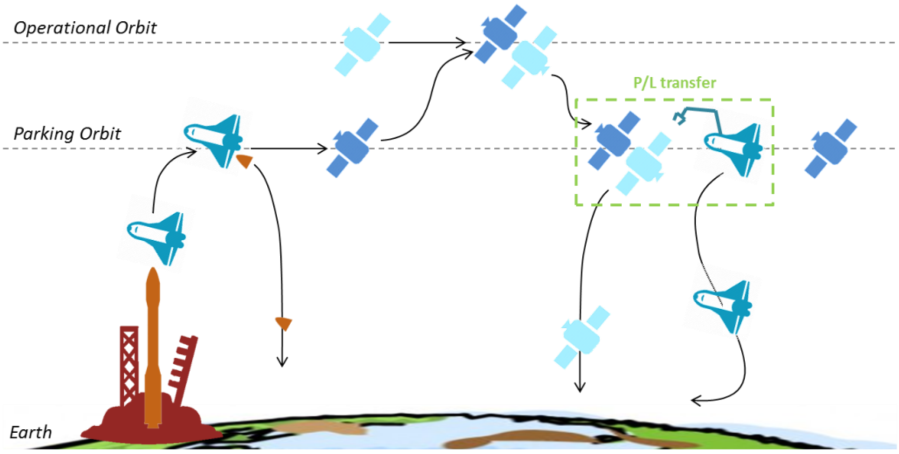


Figure 101: DRM for the payload retrieval scenario.

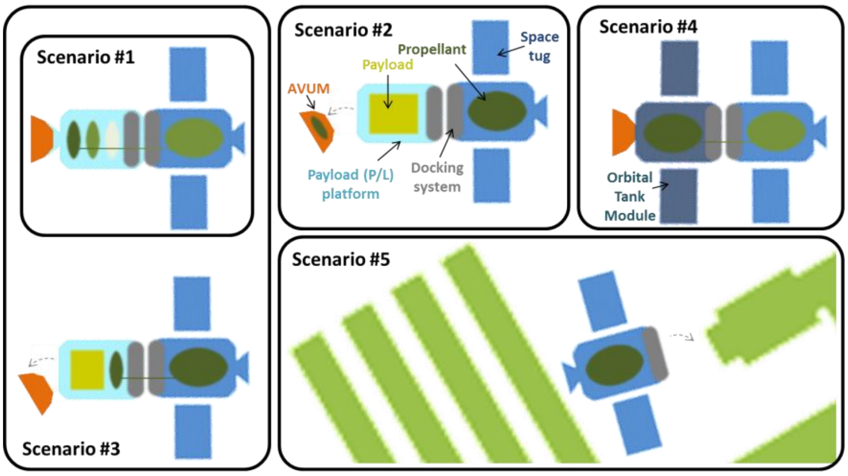


Figure 102: Options for the refuelling.

To have a refuelling option is an important feature to enhance space tug reusability. According to (Jefferies, 2015) a reusable system is able to perform multiple missions without maintenance required at sub-system or equipment level, excluding consumable commodities. Refuelling operations foreseen or not will be considered as alternatives for the BBs configurations (i.e. space tug types). In addition, only BBs with robotic systems that might have the possibility to transfer a crew only as a payload and that do not have the capability of performing re-entry will be selected for simplicity. This is in line with STRONG architecture that was mainly robotic, enlarging it to the possibility to transfer human being as a payload. Another constraint related to STRONG project is the use of electrical propulsion (Cresto Aleina, 2016d), that is also in line with the international space roadmaps and main strategies. This particular choice leads to a lower fuel consumption providing a better reliability and design simplicity than chemical systems (Cresto Aleina, 2017c), even if it offers longer transfer times that are not an issue if considering robotic systems transfers. Finally, the possibility of multiple space tug assembly will be considered to enlarge STRONG project scenario.

Finally, according to (NASA, 2010), a usual budget for the development of satellite servicing systems such as space tugs is of about 440-460 M€. This value is also in line with a mission implementing electric propulsion such as Dawn mission (Russel, 2005). Indeed, Dawn mission has had a final budget of about 400 M€ for over-costs and changes in the original architecture (Bhattacharya, 2016). For these reasons, an available budget of about 420 M€ can be supposed.

5.3. TRIS Application: Roadmap Development

Similarly as for the case of an hypersonic space transportation and re-entry system, a roadmapping process can start on the basis of the preliminary activities and following the method proposed in the previous chapters (see chapter 2 and 3 for details), i.e. TRIS.

5.3.1. Roadmap Elements Definition and Characterization Process

In (Cresto Aleina, 2016d) the main functions and the main actors of STRONG system are clearly defined, characterizing their interfaces. Considering these results, for the case study selected, there are a high number of technologies potentially applicable and, for simplicity, only some enabling TAs will be analysed. Considering the definition of a space tug, these TAs have to be related to the propulsion system and the docking or berthing system (Oda, 2012; Grover, 2008; NASA, 2010). This means focusing on, looking at (ESA, 2015b) (i.e. at TREx), "*Advanced Propulsion*", "*Automation & Robotics*", "*Advanced Structures & Mechanism Applications*" and "*GNC & Sensors*" TAs. The final list of technologies (Table 21) is obtained looking at the technologies inside every selected TAs in TREx able to fulfil the preliminary activities outputs and checking for updated according to different references such as (Messidoro, 2013). A total number of 43 technologies are achieved (i.e. 16, 6, 2 and 19 technologies respectively for each TAs).

Finally, it has to be said that the available budget selected in the previous paragraph refers to a complete case study (i.e. were every possible TAs is involved): in this example, according to (Cresto Aleina, 2017c), only 4 areas over 9 are there analysed. If a homogenous distribution of the available budget between the different TAS is supposed, the final available budget for the proposed example is of about 190 M€.

For the BBs list definition, possible variables for the BBs trade space have to come from the SoS (i.e. identifying how a space tug system interacts in its SoS architecture) and from the roadmapping activity reference system (i.e. the space tug, identifying the features that can drive its design process). Analysing TREx current BBs (Saccoccia, 2017) (i.e. the SoS level in which the analysed space tug can be located, Figure 29), 37 BBs categories have been identified.

Table 21: List of considered technologies and their features.

TECHNOLOGIES	ID	TRL @2018	CaC (Mio€)	Time (days)	Milestones (month, year, TRL)	
220 N Bi-prop.	1	8	3	1003	01/2013 (5)	10/2015 (8)
1.1 KN Bi-prop.	2	8	10	1642	01/2013 (3)	07/2017 (8)
High Performance Propulsion System	3	5	10	2557	01/2014 (2)	01/2021 (8)
6kN Bi-propellant engine (throttleable)	4	3	60	3377	01/2014 (2)	04/2023 (8)
3D printing of propulsion piping components	5	5	2	1826	01/2013 (1)	01/2018 (8)
European MPCV latch valve technology	6	5	3	1826	01/2013 (2)	01/2018 (8)
European OME and TVC for MPCV	7	5	12	1461	01/2015 (5)	01/2019 (8)
5kW High Thrust Electric Propulsion Systems	8	5	22	5295	01/2004 (3)	07/2018 (8)
High Current Cathode Technology	9	5	4	1826	01/2013 (2)	01/2018 (8)
20-30kW Electric Propulsion System	10	5	50	3468	01/2013 (2)	07/2022 (8)
Alternative Propellants	11	5	5	3287	01/2013 (2)	01/2022 (8)
20-30kW System Components	12	5	10	3468	01/2013 (2)	07/2022 (8)
5kN Bipropellant Engine (fixed thrust/storable propellant)	13	5	20	2191	01/2013 (3)	01/2019 (8)
Long life Cryogenic System	14	3	20	2191	01/2013 (2)	01/2019 (5)
Thermal Engine	15	3	20	1369	01/2015 (2)	10/2018 (5)
Auxiliary Power Units	16	2	20	3653	01/2015 (2)	01/2025 (8)
METERON	17	5	7.3	2191	01/2013 (2)	01/2019 (8)
Refuelling Robotics	18	5	8	2099	01/2013 (2)	10/2018 (8)
Capturing and deorbiting robotics	19	5	12	2556	01/2013 (2)	01/2020 (8)
Lunar Teleoperation Technologies	20	5	5	2464	01/2013 (2)	10/2019 (8)
Autonomous Control	21	5	12	3195	01/2013 (3)	10/2021 (8)
High performance computers	22	7	10	1645	07/2013 (3)	01/2018 (8)
Docking & in orbit servicing Mechanisms	23	3	20	2191	01/2013 (2)	01/2019 (5)
Electrical Propulsion pointing mechanism 20-30 kW	24	3	14	3468	01/2013 (3)	07/2022 (8)
GNC for autonomous and agile systems	25	6	15	2372	01/2013 (3)	07/2019 (8)
GNC for un-cooperative targets	26	7	6	1796	05/2013 (2)	04/2018 (8)
GNC for re-fuelling	27	4	5	2192	07/2015 (2)	07/2021 (8)
Image processing and pose estimation	28	5	3	1857	12/2014 (3)	01/2020 (8)
GNC for manned missions	29	4	3	2192	07/2015 (2)	07/2021 (8)
Control of large vehicles	30	5	3	1827	07/2015 (3)	07/2020 (8)
Advanced FDIR and health monitoring	31	6	6	1461	07/2015 (4)	07/2019 (8)
Navigation for manned systems	32	5	13	1826	01/2014 (1)	01/2019 (8)
Advanced GNC on a chip	33	4	6	2192	07/2015 (2)	07/2021 (8)
GNC data fusion and hazard avoidance	34	4	10	2192	07/2015 (2)	07/2021 (8)
Inertial Measurement Systems	35	5	10	2373	01/2014 (2)	07/2020 (8)
Navigation cameras (visible)	36	5	4	2373	01/2014 (2)	07/2020 (8)
Infrared and Ultraviolet sensors	37	5	6	2373	01/2014 (2)	07/2020 (8)
Imaging LIDAR technology for RvD	38	5	2	2373	01/2014 (2)	07/2020 (8)
Hybrid navigation sensors	39	5	6	2373	01/2014 (2)	07/2020 (8)
Multi-spectrum navigation sensors	40	5	4	2373	01/2014 (2)	07/2020 (8)
Optimization of sensors and structures for high pointing	41	5	4	2373	01/2014 (2)	07/2020 (8)
Miniaturised antennas for RF tracking	42	3	1	2557	01/2015 (2)	01/2022 (8)
Antennas embedded in thermal shield	43	3	1.5	2922	01/2015 (2)	01/2023 (8)

Between these systems can be found space exploration usual systems (e.g. robotic assemblers or tank modules), support systems (e.g. autonomous vehicles or communication networks) and ground facilities (e.g. launch facilities). Between them, also a “space tug” category can be found. To detail this system in BBs trade space, the following features are considered, achieving 8 possible types of BBs: n*umber of tugs* (i.e. single tug or multiple tug) (Messidoro, 2013), *type of RvD* (i.e. RvD with an active or a passive payload) and *reusability level* (i.e. in-space refuelling operations foreseen or not)

Following the same logic, variables for the OCs trade space are shown in Figure 103, starting again from the Functional Analysis performed for the TREx update (Figure 28) and detailing space tug level considering current market trends end strategies (NASA, 2010).

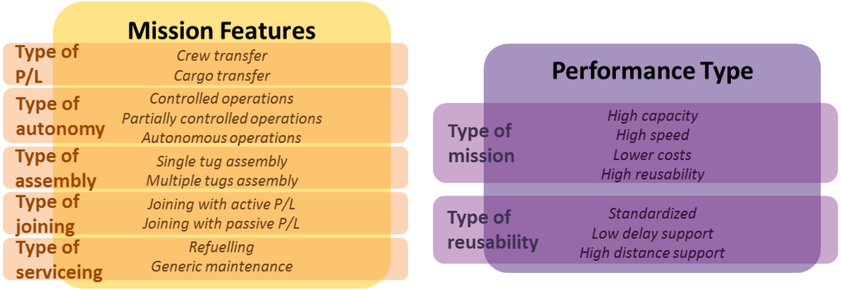


Figure 103: Lists of the two trade space variables for the OCs.

Combining every possible transfer between two defined strategic target environments (Figure 104) is possible to define every possible demonstrative and operative MCs (Cresto Aleina, 2017c), assuming not to perform demonstrative missions in MEO and GEO because too near to the maximum target. Technology maturation activities till TRL 6 are suggested in a similar process as the one proposed in paragraph 3.3.1, i.e. applying the TRL definitions (Mankins, 2009). Finally, 33 types of MCs are suggested (6 technology maturation activities, 15 demonstrative MCs and 12 operative MCs).

Acceding to (Cresto Aleina, 2016d) the following Modes of Operations have been defined: *stand-by mode* (limited at altitude higher than LEO), *check mode* (used at least in Earth Atmosphere), *handling mode* (limited at altitude higher than LEO), *docking mode* (used at least in Earth Atmosphere), *refuelling mode* (used at least in Earth Atmosphere) and *safe mode* (limited at altitude higher than LEO). Then, the Mission Phases can be the following ones (Cresto Aleina, 2016d):

maintain an orbit, increase an orbit radius, decrease orbit radius and operations. Mission Phases and Modes of Operations can be connected (Table 22).

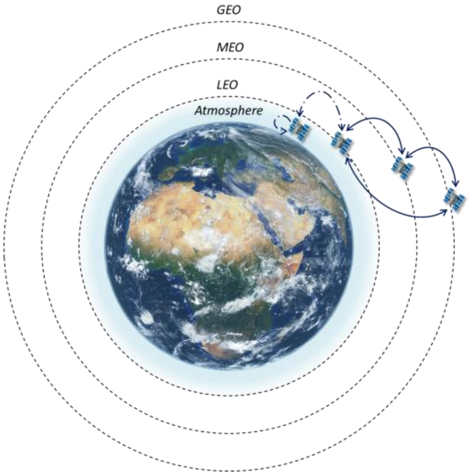


Figure 104: Scheme of the possible mission legs that can be performed in operational and demonstrative missions.

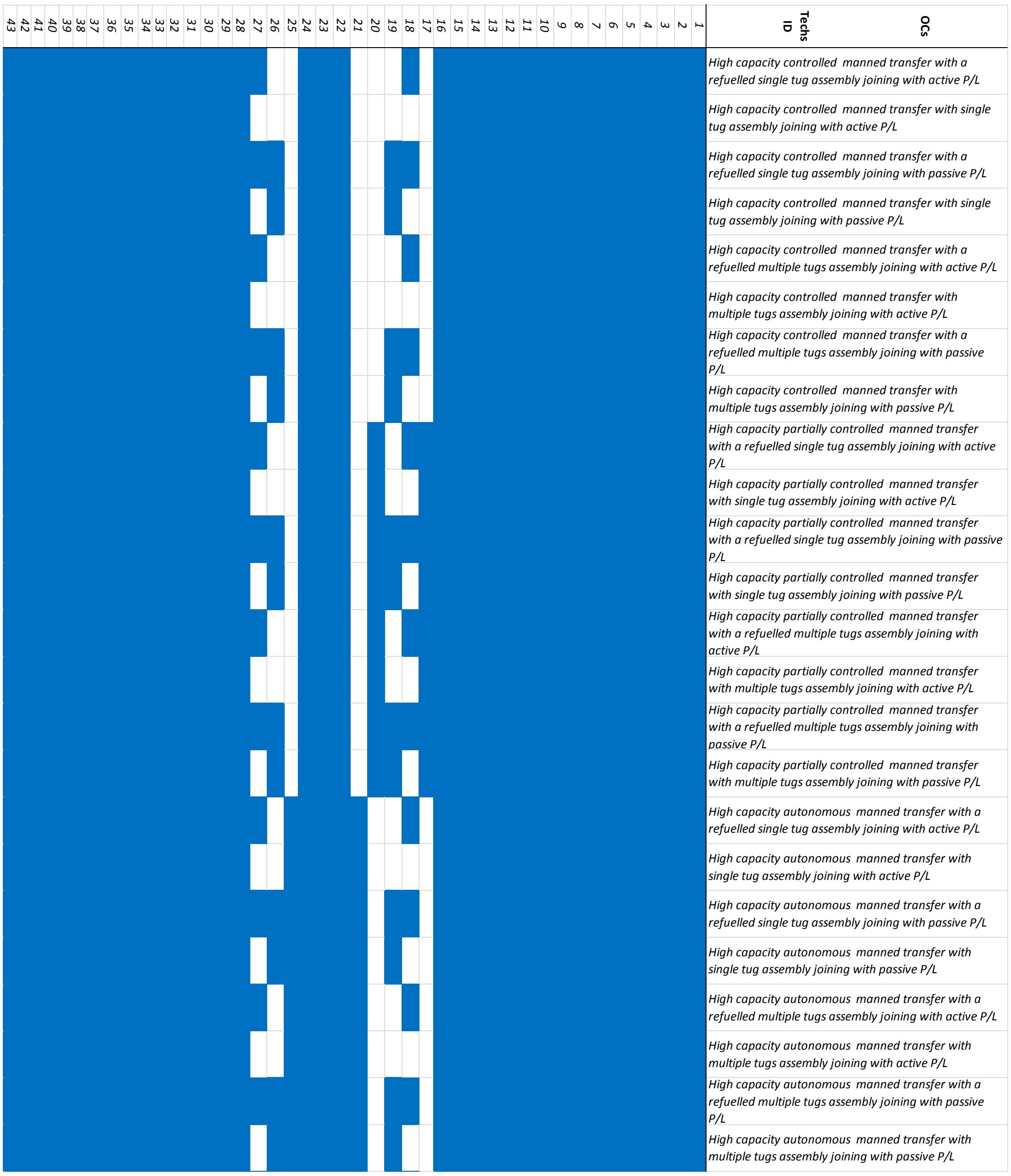
Summarizing the results, 336 OCs have been defined applying (4.1) (and eventually 77 applying (4.2)). With a similar process, 8 BBs have been defined. A list of 33 MCs types is proposed before technologies incompatibility analysis (6 technology maturation activities, 15 demonstrative MCs and 12 operative MCs). A partial number of TAs is analysed (i.e. 4), selecting 10 technology subjects from (ESA, 2015b) and 43 technologies.

Table 22: Mission Phases vs Modes of Operations.

		Mission Phases				
		Maintain an orbit	*Increase orbit radius*	*Decrease orbit radius*	*Operations*	*Atmospheric test*
Modes of Operations	*Stand-by mode*	X				
	Check mode	X	X	X	X	X
	Handling mode		X	X		X
	Docking mode				X	(X)
	Refuelling mode				X	X
	Safe mode	X	X	X	X	

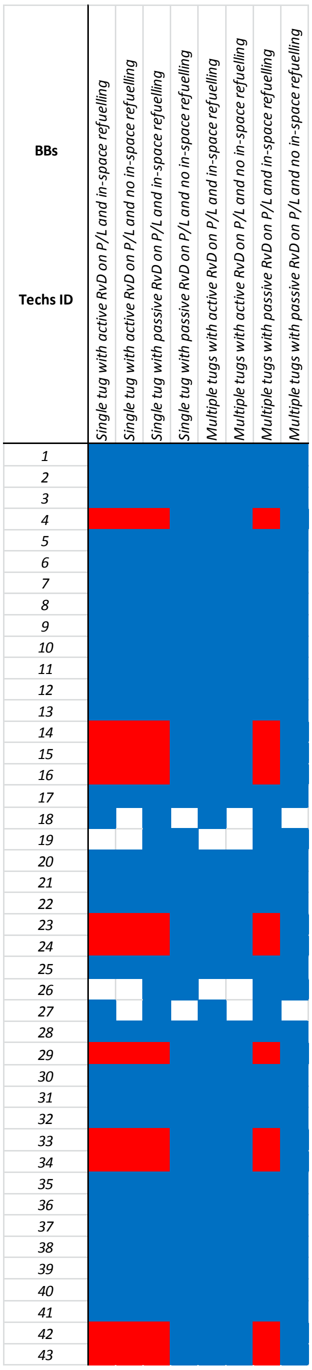
5.3.2. Applicability Analysis

At this point it is possible to derive the applicability maps (Cresto Aleina, 2017c). For simplicity in Figure 105, Figure 106 and Figure 108 are shown three of the four maps for the IXV example at the second iteration (i.e. after the elements impacts on design definition).



43	42	41	40	39	38	37	36	35	34	33	32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	Techs ID OCs
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■	■				■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity controlled manned transfer with a refuelled single tug assembly joining with active P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■	■						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity controlled manned transfer with single tug assembly joining with active P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■			■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity controlled manned transfer with a refuelled single tug assembly joining with passive P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■		■	■	■			■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity controlled manned transfer with single tug assembly joining with passive P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■	■				■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity controlled manned transfer with a refuelled multiple tugs assembly joining with active P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■	■						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity controlled manned transfer with multiple tugs assembly joining with active P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■			■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity controlled manned transfer with a refuelled multiple tugs assembly joining with passive P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■		■	■	■			■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity controlled manned transfer with multiple tugs assembly joining with passive P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity partially controlled manned transfer with a refuelled single tug assembly joining with active P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■	■		■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity partially controlled manned transfer with single tug assembly joining with active P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity partially controlled manned transfer with a refuelled single tug assembly joining with passive P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■		■	■	■		■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity partially controlled manned transfer with single tug assembly joining with passive P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity partially controlled manned transfer with a refuelled multiple tugs assembly joining with active P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■	■		■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity partially controlled manned transfer with multiple tugs assembly joining with active P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity partially controlled manned transfer with a refuelled multiple tugs assembly joining with passive P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■		■	■	■		■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity partially controlled manned transfer with multiple tugs assembly joining with passive P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■			■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity autonomous manned transfer with a refuelled single tug assembly joining with active P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■	■	■	■					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity autonomous manned transfer with single tug assembly joining with active P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity autonomous manned transfer with a refuelled single tug assembly joining with passive P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■		■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity autonomous manned transfer with single tug assembly joining with passive P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■			■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity autonomous manned transfer with a refuelled multiple tugs assembly joining with active P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■	■	■	■					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity autonomous manned transfer with multiple tugs assembly joining with active P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity autonomous manned transfer with a refuelled multiple tugs assembly joining with passive P/L
■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■		■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	High capacity autonomous manned transfer with multiple tugs assembly joining with passive P/L

Figure 105: Applicability map between technologies and OCs.
For simplicity, only OCs related to the "high capacity" Performance Type are shown.

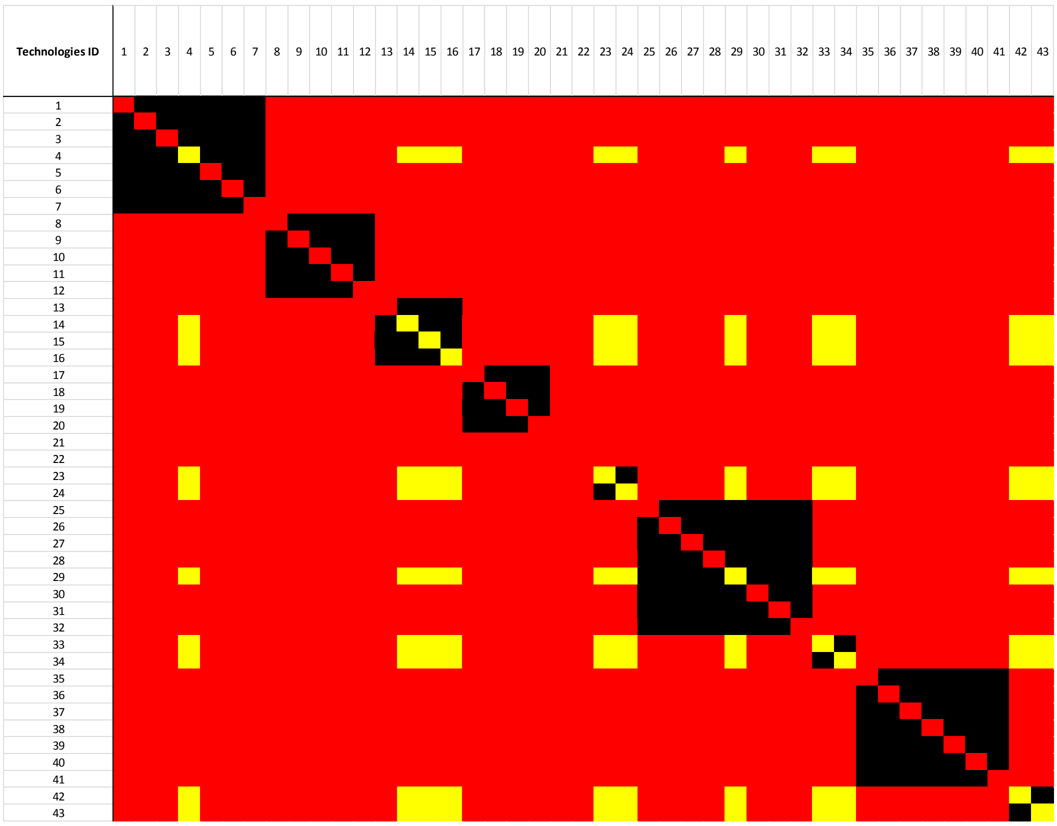


BBs Techs ID	Single tug with active RvD on P/L and in-space refuelling	Single tug with active RvD on P/L and no in-space refuelling	Single tug with passive RvD on P/L and in-space refuelling	Single tug with passive RvD on P/L and no in-space refuelling	Multiple tugs with active RvD on P/L and in-space refuelling	Multiple tugs with active RvD on P/L and no in-space refuelling	Multiple tugs with passive RvD on P/L and in-space refuelling	Multiple tugs with passive RvD on P/L and no in-space refuelling
1	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
2	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
3	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
4	🟥	🟥	🟥	🟦	🟦	🟦	🟥	🟦
5	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
6	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
7	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
8	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
9	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
10	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
11	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
12	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
13	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
14	🟥	🟥	🟥	🟦	🟦	🟦	🟥	🟦
15	🟥	🟥	🟥	🟦	🟦	🟦	🟥	🟦
16	🟥	🟥	🟥	🟦	🟦	🟦	🟥	🟦
17	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
18	🟦	⬜	🟦	⬜	🟦	⬜	🟦	⬜
19	⬜	⬜	🟦	🟦	⬜	⬜	🟦	🟦
20	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
21	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
22	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
23	🟥	🟥	🟥	🟦	🟦	🟦	🟥	🟦
24	🟥	🟥	🟥	🟦	🟦	🟦	🟥	🟦
25	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
26	⬜	⬜	🟦	🟦	⬜	⬜	🟦	🟦
27	🟦	⬜	🟦	⬜	🟦	⬜	🟦	⬜
28	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
29	🟥	🟥	🟥	🟦	🟦	🟦	🟥	🟦
30	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
31	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
32	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
33	🟥	🟥	🟥	🟦	🟦	🟦	🟥	🟦
34	🟥	🟥	🟥	🟦	🟦	🟦	🟥	🟦
35	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
36	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
37	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
38	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
39	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
40	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
41	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
42	🟥	🟥	🟥	🟦	🟦	🟦	🟥	🟦
43	🟥	🟥	🟥	🟦	🟦	🟦	🟥	🟦

Figure 106: Applicability map between technologies and BBs.

Technology ID	Analyzed or not	TRL	Actual target environment ID	Required target environment ID	Environment evaluation	AD2	Likelihood	Total probability	Consequence	Max allocated costs increase
1		8	1	2	SIMPLE	4	1	12%	5	20%
2		8	1	2	SIMPLE	4	1	12%	5	20%
3		5	1	2	SIMPLE	6	2	36%	5	20%
4		3	1	2	SIMPLE	6	2	36%	5	20%
5		5	1	2	SIMPLE	6	2	36%	5	20%
6		5	1	2	SIMPLE	6	2	36%	5	20%
7		5	1	2	SIMPLE	6	2	36%	5	20%
8		5	1	2	SIMPLE	5	2	36%	4	10%
9		5	1	2	SIMPLE	5	2	36%	4	10%
10		5	1	2	SIMPLE	5	2	36%	4	10%
11		5	1	2	SIMPLE	5	2	36%	4	10%
12		5	1	2	SIMPLE	5	2	36%	4	10%
13		5	1	2	SIMPLE	5	2	36%	4	10%
14		3	1	2	SIMPLE	4	1	12%	5	20%
15		3	1	2	SIMPLE	4	1	12%	5	20%
16		2	1	2	SIMPLE	4	1	12%	5	20%
17		5	1	2	SIMPLE	5	2	36%	4	10%
18		5	1	2	SIMPLE	5	2	36%	4	10%
19		5	1	2	SIMPLE	5	2	36%	4	10%
20		5	1	2	SIMPLE	5	2	36%	4	10%
21		5	1	2	SIMPLE	5	2	36%	4	10%
22		7	1	2	SIMPLE	6	2	36%	5	20%
23		3	1	2	SIMPLE	4	1	12%	5	20%
24		3	1	2	SIMPLE	4	1	12%	5	20%
25		6	1	2	SIMPLE	5	2	36%	4	10%
26		7	1	2	SIMPLE	6	2	36%	5	20%
27		4	1	2	SIMPLE	5	2	36%	4	10%
28		5	1	2	SIMPLE	5	2	36%	4	10%
29		4	1	2	SIMPLE	5	2	36%	4	10%
30		5	1	2	SIMPLE	5	2	36%	4	10%
31		6	1	2	SIMPLE	5	2	36%	4	10%
32		5	1	2	SIMPLE	5	2	36%	4	10%
33		4	1	2	SIMPLE	5	2	36%	4	10%
34		4	1	2	SIMPLE	5	2	36%	4	10%
35		5	1	2	SIMPLE	5	2	36%	4	10%
36		5	1	2	SIMPLE	5	2	36%	4	10%
37		5	1	2	SIMPLE	5	2	36%	4	10%
38		5	1	2	SIMPLE	5	2	36%	4	10%
39		5	1	2	SIMPLE	5	2	36%	4	10%
40		5	1	2	SIMPLE	5	2	36%	4	10%
41		5	1	2	SIMPLE	5	2	36%	4	10%
42		3	1	2	SIMPLE	4	1	12%	5	20%
43		3	1	2	SIMPLE	4	1	12%	5	20%

Figure 107: AD2 analysis results.



Technologies ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
1	🟥	⬛	⬛	⬛	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
2	⬛	🟥	⬛	⬛	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
3	⬛	⬛	🟥	⬛	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
4	⬛	⬛	⬛	🟨	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨
5	⬛	⬛	⬛	⬛	🟥	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
6	⬛	⬛	⬛	⬛	⬛	🟥	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
7	⬛	⬛	⬛	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
8	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
9	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	🟥	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
10	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	🟥	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
11	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	🟥	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
12	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
13	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
14	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	🟨	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨
15	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	🟨	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨
16	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨
17	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
18	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	🟥	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
19	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	🟥	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
20	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
21	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
22	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
23	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟨	⬛	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨
24	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	⬛	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨
25	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
26	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	🟥	⬛	⬛	⬛	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
27	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	🟥	⬛	⬛	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
28	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	🟥	⬛	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
29	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	⬛	⬛	⬛	⬛	🟨	⬛	⬛	⬛	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨
30	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	🟥	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
31	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	⬛	🟥	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
32	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	⬛	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
33	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟨	⬛	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨
34	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	⬛	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨
35	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	⬛	🟥	🟥
36	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	🟥	⬛	⬛	⬛	⬛	⬛	🟥	🟥
37	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	🟥	⬛	⬛	⬛	⬛	🟥	🟥
38	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	🟥	⬛	⬛	⬛	🟥	🟥
39	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	🟥	⬛	⬛	🟥	🟥
40	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	🟥	⬛	🟥	🟥
41	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	⬛	🟥	🟥	🟥
42	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	⬛
43	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	🟨

Figure 108: Applicability map between technologies (compatibility analysis).

Indeed, the applicability map between MCs and technologies does not show any incompatibility, according to the Modes of Operations analysis. It has to be said that, defining the Mission Phases on the basis of activities that the tug might perform, it is possible to have a link also between OCs and MCs, looking at the possible assembly strategies (Messidoro, 2013). In Figure 107 are shown the main results achieved, for simplicity only data about AD2 estimation are provided.

It has to be noticed that, thanks to Figure 108, every operative and demo MCs has to be considered twice for technologies incompatibilities. In order so solve incompatibilities, the incompatible technologies applied in a same MC have to be divided into two different MCs that are equal but with different technologies applied. This is only a proposal to a TRIS user that will be able to avoid this division.

5.3.3. Sensitivity Analysis

Starting from a nominal set of labels (i.e. required level at 2 and applicable one at 1) and looking at about the 50% of differences distributions (Figure 109), a required weight of 1.8 and an applicable one of 1 are proposed.

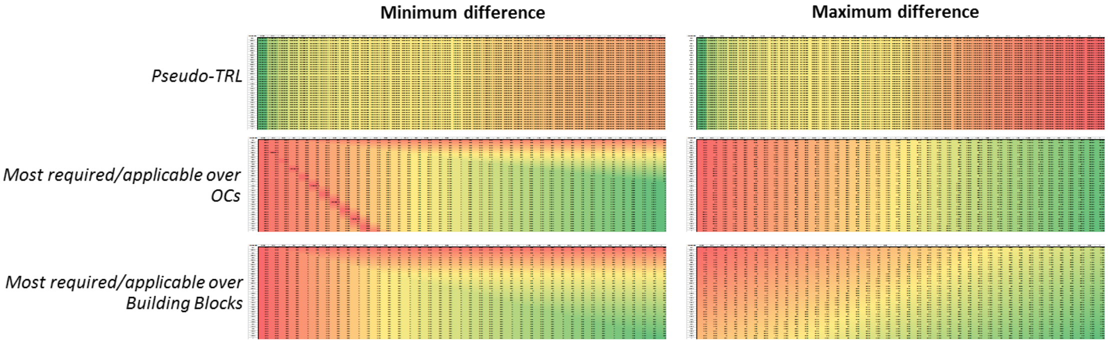


Figure 109: Sensitivity analysis tables.

5.3.4. Prioritization Studies

Also for this last case study and based on the previous phases results, the main purpose of this phase is to rank technologies and MCs and to define impacts on design for technologies, BBs and OCs, in order to suggest and weight preferable paths to be followed in the roadmap definition.

5.3.4.1. Roadmap elements impact on design analysis

Following the process explained in paragraph 3.3.4.1 with the criteria listed in paragraph 5.2 and choosing to evaluate FoMs on the first 12 technologies thanks to a sensitivity analysis (Figure 110), the optimal solution is reached considering as able to create enabling technologies criteria #4 and #5 and as able to create enhancing technologies criteria #1, #2 and #3. For this combination, the TRL cost-effectiveness is at 0.20, the average costs increase is at 0.19 and the total probability of failure is at 0.95 (e.g. a total value of 0.42). The results are reported in Figure 116. As a result, 11 enabling technologies over 43 are defined.

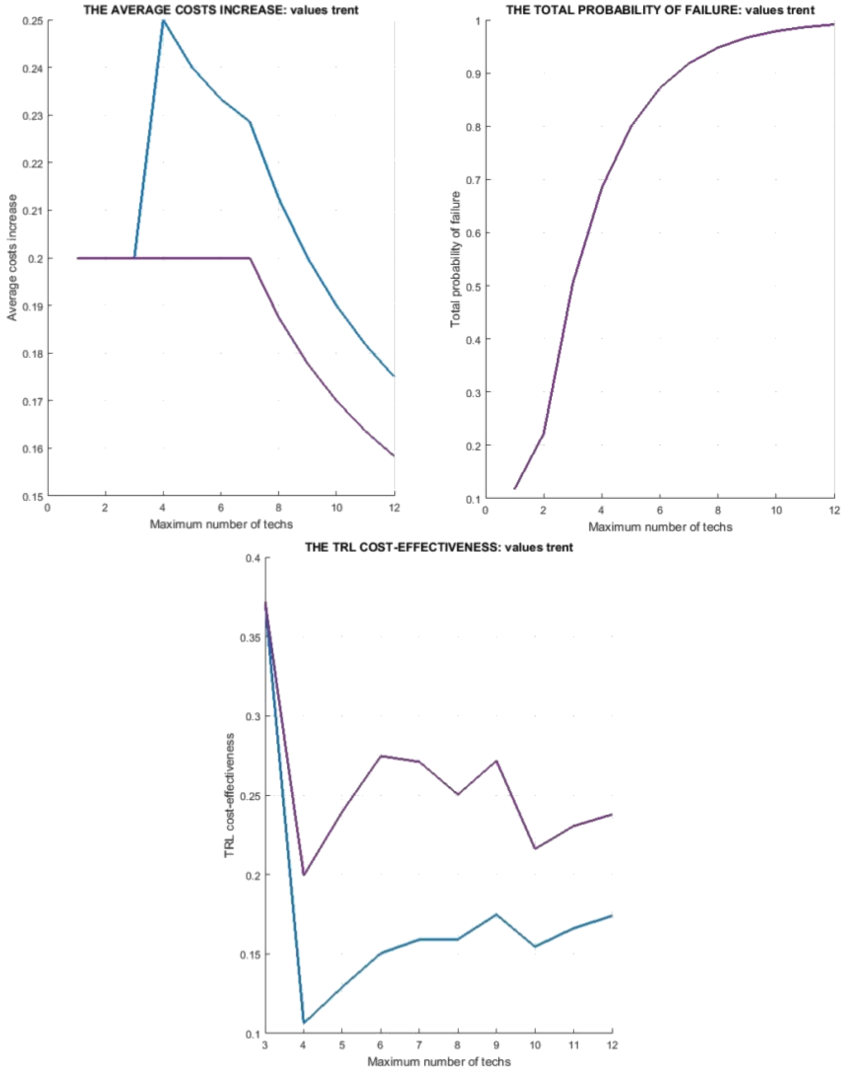


Figure 110: Sensitivity analysis results.
Different colours means different criteria combinations.

On the basis of the methodology propose din paragraph 3.3.4.1 and applying the same criteria listed in paragraph 4.3.4.1 to the BBs (Figure 111), it is possible to define 4 enabling BBs (i.e. *Single tug with active RvD on P/L and in-space refuelling*, *Single tug with active RvD on P/L and no in-space refuelling*, *Single tug with passive RvD on P/L and in-space refuelling* and *Multiple tugs with passive RvD on P/L and in-space refuelling*) and 4 enhancing BBs (i.e. *Single tug with passive RvD on P/L and no in-space refuelling*, *Multiple tugs with active RvD on P/L and in-space refuelling*, *Multiple tugs with active RvD on P/L and no in-space refuelling* and *Multiple tugs with passive RvD on P/L and no in-space refuelling*). Similarly, it is possible to define 10 enabling OCs and 326 enhancing

OCs with no OCs not important (Figure 112). For simplicity, Table 24 shows the objectives only for the OCs related to the “high capacity” Performance Type.

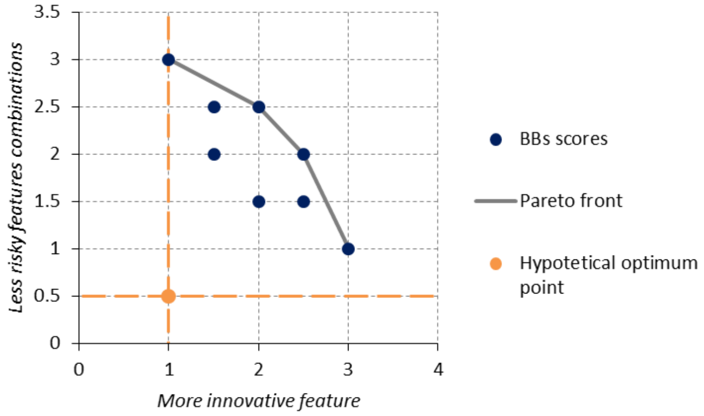


Figure 111: Pareto analysis performed over the BBs list.

Table 23: Results for the impact on design analysis criteria on BBs.

BBs	Obj 1	Obj 2
Single tug with active RvD on P/L and in-space refuelling	2	2.5
Single tug with active RvD on P/L and no in-space refuelling	1	3
Single tug with passive RvD on P/L and in-space refuelling	2.5	2
Single tug with passive RvD on P/L and no in-space refuelling	1.5	2.5
Multiple tugs with active RvD on P/L and in-space refuelling	2.5	1.5
Multiple tugs with active RvD on P/L and no in-space refuelling	1.5	2
Multiple tugs with passive RvD on P/L and in-space refuelling	3	1
Multiple tugs with passive RvD on P/L and no in-space refuelling	2	1.5

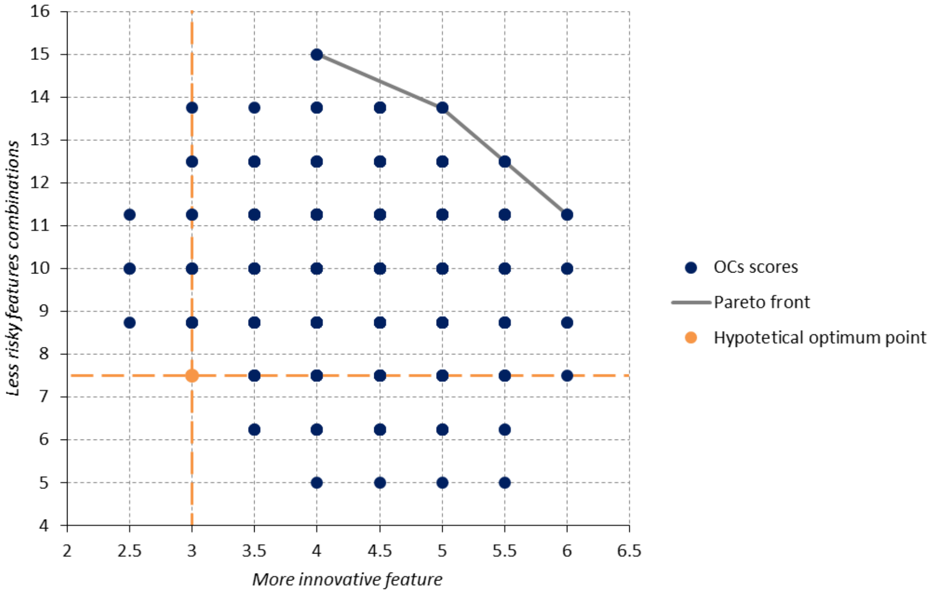


Figure 112: Pareto analysis performed over the OCs list.

Table 24: Results for the impact on design analysis criteria on OCs.
For simplicity, only OCs related to the "high capacity" Performance Type are shown

OCs	**Obj 1**	**Obj 2**
High capacity crtl manned transfer with a refuelled single tug joining with active P/L	4	10
High capacity crtl manned transfer with single tug joining with active P/L	3,5	11,25
High capacity crtl manned transfer with a refuelled single tug joining with passive P/L	4,5	8,75
High capacity crtl manned transfer with single tug joining with passive P/L	4	10
High capacity crtl manned transfer with refuelled multiple tugs joining with active P/L	4	11,25
High capacity crtl manned transfer with multiple tugs joining with active P/L	3,5	12,5
High capacity crtl manned transfer with refuelled multiple tugs joining with passive P/L	4,5	10
High capacity crtl manned transfer with multiple tugs joining with passive P/L	4	11,25
High capacity partially crtl manned transfer with a refuelled single tug joining with active P/L	4,5	8,75
High capacity partially crtl manned transfer with single tug joining with active P/L	4	10
High capacity partially crtl manned transfer with a refuelled single tug joining with passive P/L	5	7,5
High capacity partially crtl manned transfer with single tug joining with passive P/L	4,5	8,75
High capacity partially crtl manned transfer with refuelled multiple tugs joining with active P/L	4,5	10
High capacity partially crtl manned transfer with multiple tugs joining with active P/L	4	11,25
High capacity partially crtl manned transfer with refuelled multiple tugs joining with pass. P/L	5	8,75
High capacity partially crtl manned transfer with multiple tugs joining with passive P/L	4,5	10
High capacity autonomous manned transfer with a refuelled single tug joining with active P/L	5	8,75
High capacity autonomous manned transfer with single tug joining with active P/L	4,5	10
High capacity autonomous manned transfer with a refuelled single tug joining with passive P/L	5,5	7,5
High capacity autonomous manned transfer with single tug joining with passive P/L	5	8,75
High capacity autonomous manned transfer with refuelled multiple tugs joining with active P/L	5	10
High capacity autonomous manned transfer with multiple tugs joining with active P/L	4,5	11,25
High capacity autonomous manned transfer with refuelled multiple tugs joining with pass. P/L	5,5	8,75
High capacity autonomous manned transfer with multiple tugs joining with passive P/L	5	10

5.3.4.2. Technologies ranking

The ranking of the technologies is achieved choosing to evaluate FoMs on the first 12 technologies thanks to a sensitivity analysis (Figure 113), the optimal criteria combination with all the four criteria applied is considering this particular order: #4, #1, #2 and #3. For this combination, the TRL cost-effectiveness is at 1.36, the average costs increase is at 0.14 and the total probability of failure is at 0.995 (e.g. a total value of 0.04). The results are shown in Figure 116.

5.3.4.3. MCs ranking

The prioritization of MCs has been performed applying these criteria and in this order, with the main purpose of simplifying the planning definition:

1. *By target environment distance from ground* in ascending order;
2. *By number of Modes of Operations* in descending order;
3. *By number of applicable/required technologies* in descending order;
4. *By minimum TRL required* in ascending order.

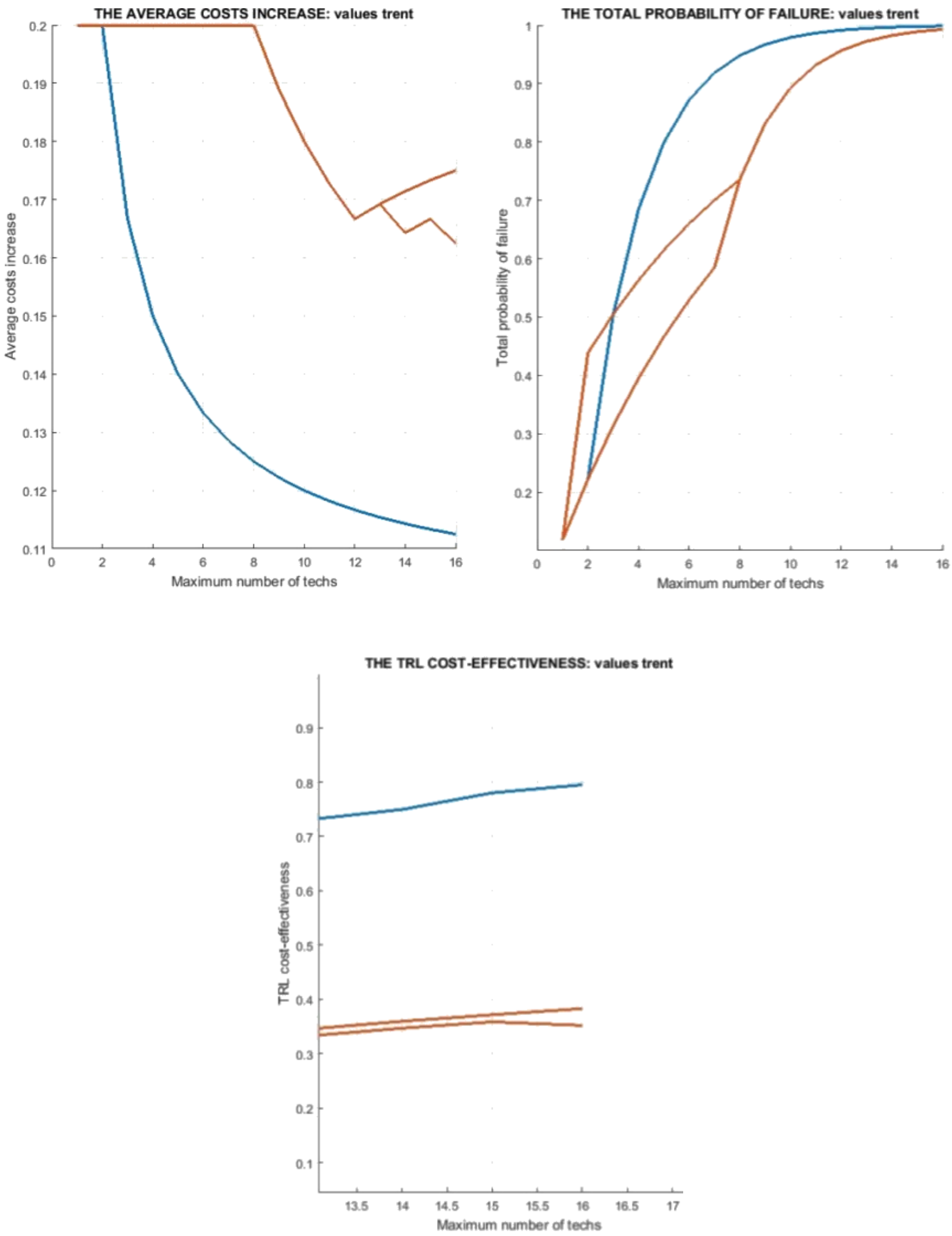


Figure 113: Sensitivity analysis results.
Different colours means different criteria combinations.

It has to be noticed that finding data about the required budget is difficult, especially for a mission to be proposed. For simplicity, the criterion related to this value (i.e. “*by required budget* in ascending order” considered in the previous chapter) has been neglected, considering negligible the proposed MCs differences in innovation level and complexity. Following this criteria order, high priority is given to MCs with higher number of technologies that take place near Earth, minimizing not only the final number or MC required in the planning, but also the costs. For example, technology maturation activities such as "*M2. Concept application/formulation*" has a high priority, while operative MCs, such as a transfer between MEO and GEO has a low priority.

5.3.5. Planning Definition

Starting from the data derived until now and considering the data present in TREx, it is possible to propose a planning. Similarly as the previous case study, not all the data required are present in TREx and some of them have to be estimated. Figure 114 shows the relationship between US DoD lifecycle phases, technology maturity (i.e. TRL), TRL transit costs and duration and it has been derived applying the TRL transit duration proposed in Figure 59 to a timeframe of 10 years as already explained and the CaC division proposed in Figure 56.

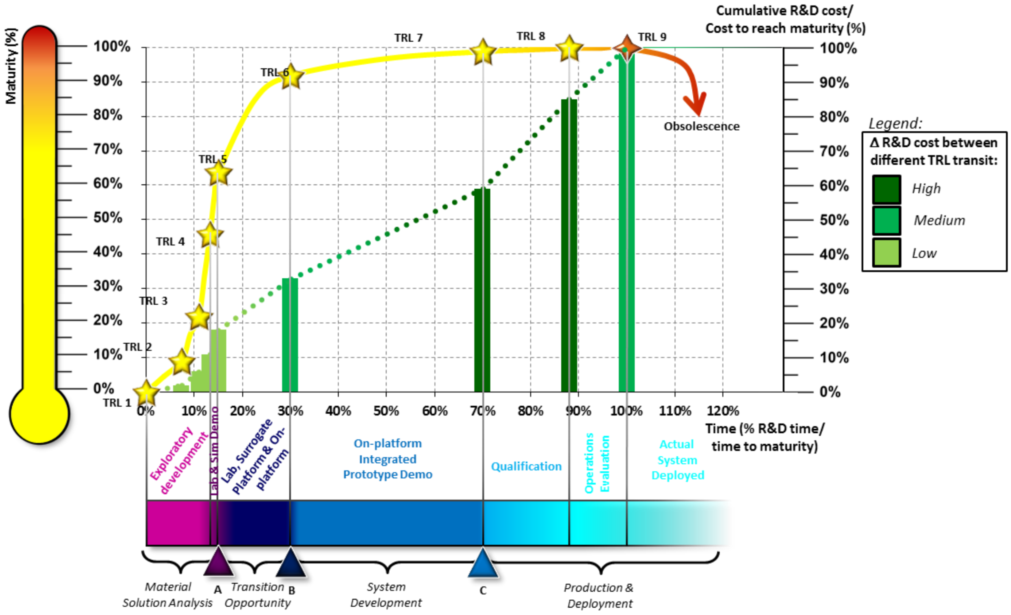


Figure 114: Project phases and generalized expectation for the TRL and CaC evolution.

Supposing to keep TRL 8 as the maximum TRL and distributing the available budget in the different TRL transits, 6 technologies are excluded in the planning (e.g. "*High Current Cathode Technology*", at the 9th place of priority and with a CaC of about 22 M€), while 3 cannot reach the desired maturity (e.g. "*Partial development, Auxiliary Power Units*" able to reach TRL 6 and at the 36th place of priority) and only 33 technologies can reach TRL 8 (Figure 115). The final budget of 189.86 M€ is required, performing 111 TRL transit between all the technologies involved.

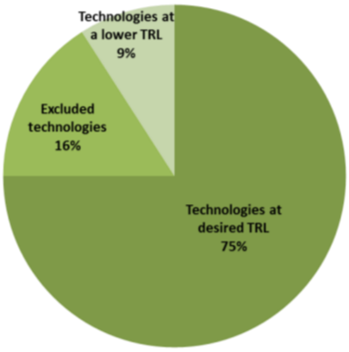
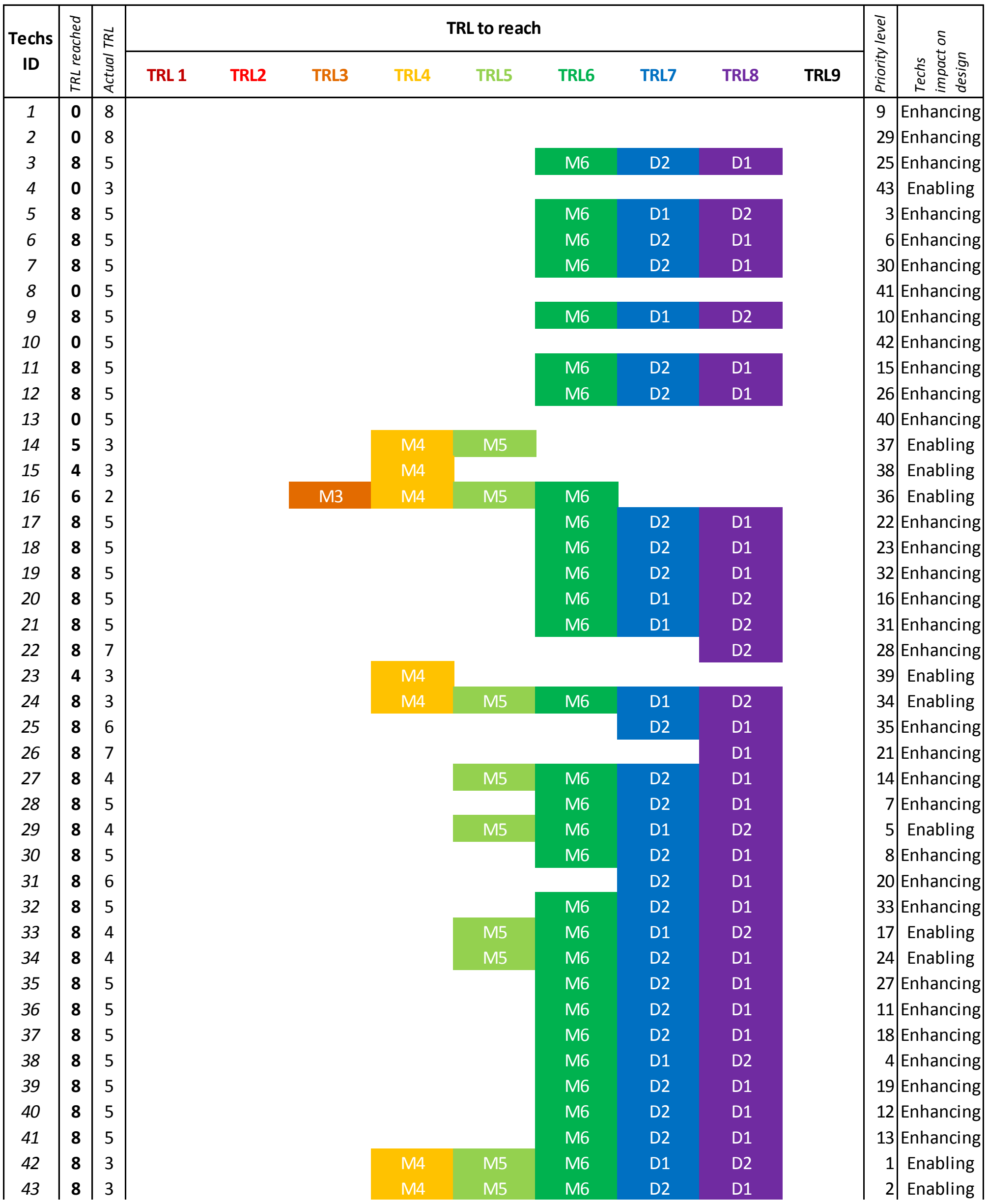


Figure 115: Summary of the technologies status at the end of the nominal roadmap.

Figure 116 shows also the MCs selected in the planning, where only 6 missions types are there suggested:

1. A 4 types technology maturation activities to reach TRL 6 to be performed in laboratory for each technology taken separately (i.e. *Analytical/ experimental proof* (M3), *Laboratory components/ breadboard validation* (M4), *Components/ breadboard validation in relevant (not controlled) environment* (M5), *Model demonstration in relevant (not controlled) environment* (M6));
2. A demonstrative mission to reach TRL 7 (i.e. a transfer missions between LEO and Earth atmosphere, considering the minimum altitude at which an orbit is possible, i.e. 100 km);
3. A demonstrative mission to reach TRL 8 (i.e. a transfer missions between Earth atmosphere and LEO).

While a single operative mission can be supposed, for the demo mission the possible incompatibility between the technology with ID #2 and the technology with ID #3 has still to be studied and for this reason two separate MCs are there supposed. It has to be noticed that, in both cases being the same MC able to perform both the TRL transit between 6 and 7 and the one between 7 and 8, a single mission can be proposed to perform the TRL transit between 6 and 8. This choice is left to the user, having a higher risk. Finally, looking at the TRL transit durations is possible to propose a schedule (Figure 117), to be performed between the 1st January 2017 and the 16th December 2026.



Techs ID	TRL reached	Actual TRL	TRL to reach									Priority level	Techs impact on design
			TRL 1	TRL2	TRL3	TRL4	TRL5	TRL6	TRL7	TRL8	TRL9		
1	0	8										9	Enhancing
2	0	8										29	Enhancing
3	8	5						M6	D2	D1		25	Enhancing
4	0	3										43	Enabling
5	8	5						M6	D1	D2		3	Enhancing
6	8	5						M6	D2	D1		6	Enhancing
7	8	5						M6	D2	D1		30	Enhancing
8	0	5										41	Enhancing
9	8	5						M6	D1	D2		10	Enhancing
10	0	5										42	Enhancing
11	8	5						M6	D2	D1		15	Enhancing
12	8	5						M6	D2	D1		26	Enhancing
13	0	5										40	Enhancing
14	5	3				M4	M5					37	Enabling
15	4	3				M4						38	Enabling
16	6	2			M3	M4	M5	M6				36	Enabling
17	8	5						M6	D2	D1		22	Enhancing
18	8	5						M6	D2	D1		23	Enhancing
19	8	5						M6	D2	D1		32	Enhancing
20	8	5						M6	D1	D2		16	Enhancing
21	8	5						M6	D1	D2		31	Enhancing
22	8	7								D2		28	Enhancing
23	4	3				M4						39	Enabling
24	8	3				M4	M5	M6	D1	D2		34	Enabling
25	8	6							D2	D1		35	Enhancing
26	8	7								D1		21	Enhancing
27	8	4					M5	M6	D2	D1		14	Enhancing
28	8	5						M6	D2	D1		7	Enhancing
29	8	4					M5	M6	D1	D2		5	Enabling
30	8	5						M6	D2	D1		8	Enhancing
31	8	6							D2	D1		20	Enhancing
32	8	5						M6	D2	D1		33	Enhancing
33	8	4					M5	M6	D1	D2		17	Enabling
34	8	4					M5	M6	D2	D1		24	Enabling
35	8	5						M6	D2	D1		27	Enhancing
36	8	5						M6	D2	D1		11	Enhancing
37	8	5						M6	D2	D1		18	Enhancing
38	8	5						M6	D1	D2		4	Enhancing
39	8	5						M6	D2	D1		19	Enhancing
40	8	5						M6	D2	D1		12	Enhancing
41	8	5						M6	D2	D1		13	Enhancing
42	8	3				M4	M5	M6	D1	D2		1	Enabling
43	8	3				M4	M5	M6	D2	D1		2	Enabling

Figure 116: MCs choice for the TRL increase path.

Technologies		**TRL**							
ID	*Actual TRL*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	*8*								
2	*8*								
3	*5*					01/01/2017	21/04/2018	09/07/2024	10/11/2026
4	*3*								
5	*5*					01/01/2017	08/11/2017	27/09/2024	16/12/2026
6	*5*					01/01/2017	06/12/2017	09/07/2024	10/11/2026
7	*5*					01/01/2017	28/10/2017	09/07/2024	10/11/2026
8	*5*								
9	*5*					01/01/2017	06/12/2017	27/09/2024	16/12/2026
10	*5*								
11	*5*					01/01/2017	03/09/2018	09/07/2024	10/11/2026
12	*5*					01/01/2017	07/10/2018	09/07/2024	10/11/2026
13	*5*								
14	*3*			01/01/2017	04/03/2017	22/04/2017			
15	*3*			01/01/2017	09/02/2017				
16	*2*		01/01/2017	12/06/2017	25/09/2017	15/12/2017	25/10/2019		
17	*5*					01/01/2017	12/02/2018	09/07/2024	10/11/2026
18	*5*					01/01/2017	26/01/2018	09/07/2024	10/11/2026
19	*5*					01/01/2017	21/04/2018	09/07/2024	10/11/2026
20	*5*					01/01/2017	03/04/2018	27/09/2024	16/12/2026
21	*5*					01/01/2017	14/09/2018	27/09/2024	16/12/2026
22	*7*							27/09/2024	16/12/2026
23	*3*			01/01/2017	04/03/2017				
24	*3*			01/01/2017	14/04/2017	04/07/2017	10/05/2019	27/09/2024	16/12/2026
25	*6*						25/10/2019	09/07/2024	10/11/2026
26	*7*							27/09/2024	10/11/2026
27	*4*				01/01/2017	18/02/2017	02/04/2018	09/07/2024	10/11/2026
28	*5*					01/01/2017	28/12/2017	09/07/2024	10/11/2026
29	*4*				01/01/2017	18/02/2017	02/04/2018	27/09/2024	16/12/2026
30	*5*					01/01/2017	22/12/2017	09/07/2024	10/11/2026
31	*6*						25/10/2019	09/07/2024	10/11/2026
32	*5*					01/01/2017	08/11/2017	09/07/2024	10/11/2026
33	*4*				01/01/2017	18/02/2017	02/04/2018	27/09/2024	16/12/2026
34	*4*				01/01/2017	18/02/2017	02/04/2018	09/07/2024	10/11/2026
35	*5*					01/01/2017	18/03/2018	09/07/2024	10/11/2026
36	*5*					01/01/2017	18/03/2018	09/07/2024	10/11/2026
37	*5*					01/01/2017	18/03/2018	09/07/2024	10/11/2026
38	*5*					01/01/2017	18/03/2018	27/09/2024	16/12/2026
39	*5*					01/01/2017	18/03/2018	09/07/2024	10/11/2026
40	*5*					01/01/2017	18/03/2018	09/07/2024	10/11/2026
41	*5*					01/01/2017	18/03/2018	09/07/2024	10/11/2026
42	*3*			01/01/2017	14/03/2017	10/05/2017	29/08/2018	27/09/2024	16/12/2026
43	*3*			01/01/2017	25/03/2017	29/05/2017	23/11/2018	09/07/2024	10/11/2026

Figure 117: Schedule definition.

5.3.6. Results Evaluation

Table 25 shows the main results obtained for the TRL to reach sensitivity analysis. As for the previous case study, decreasing the TRL to be reached it is possible include more technologies or the final budget employed. It has to be noticed that the data are missing in TREx about TRL 9 and this level is there neglected because not precise.

Looking at out of nominal situations, the delays are potentially between 0 and 34 years with a statistic average of 17 years and with higher frequency between 9 and 25 years. A delay of 12 years is at the 30th percentile, is the same percentile of the previous example is assumed.

Table 25: TRL to reach sensitivity analysis.

TRL to reach	N of TRL variations	Techs involved	Techs at final TRL	Techs already at TRL	Cost (M€)	Cost (%)
8	111	33	33	2	189.86	100%
7	92	37	37	4	188.26	99%
6	58	37	37	6	102.35	54%
5	21	12	12	31	25.72	14%
4	9	8	8	35	10.43	5%
3	1	1	1	42	0.96	1%
2	0	0	0	43	0	0%

Additionally, a draft risk analysis has been performed following the method proposed in 3.3.6.1 (Figure 107). Thanks to this analysis is possible to estimate a total allocated cost increase of about 25 M€.

Finally, it has to be said that, even if no example exists with enough data to be compared to the presented case study, the data achieved are similar to the studies performed before and to what is present in literature in terms of costs, timing and choices. In addition, using as an example a single technology it is possible to compare the ESA current roadmap for this technology, with the roadmap defined for it after the hypothesis of a change of priority due to the necessity to have a reusable space tug in Earth Vicinity. A possible example can be "Auxiliary Power Units" technology. Indeed, according to ESA, this technology maturation has the following main milestones:

- TRL 3 at the beginning of 2015;
- TRL 5 at the beginning of 2018;
- TRL 8 at the beginning of 2025.

Other ESA roadmap data are shown in Table 21. As you can see, the analysed technology has a similar trend as the one proposed, achieving the maximum technological maturation around 2025.

5.4. TRIS Application: Roadmap Visualization and Update

Once the technology roadmap definition process is completed, all data need to be updated and (at least periodically) reviewed. TREx, if linked to a tool based on TRIS, will play an important role in the update of the roadmap elements after the roadmap definition and in the continuous update of the roadmap after this first iteration.

Figure 118 shows the nominal roadmap achieved for the case in which a step-by-step approach is proposed for the TRL increase path. For simplicity, the roadmap for every single technology is not reported, but only a simplified summary of it. For the schedule for every single technology, please refer to Figure 116 and Figure 117.

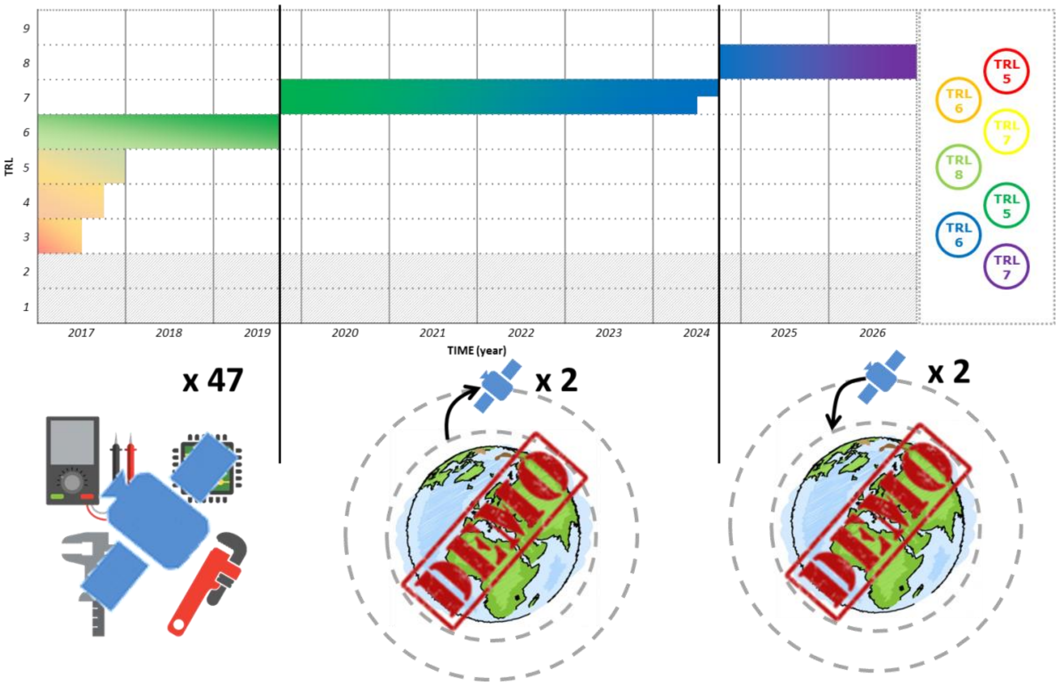


Figure 118: Simplified example of graphical view of the roadmap in case of a step-by-step approach for the TRL increase path.

5.5. Highlights

- ✓ TRIS has been applied to derive a technology roadmap for a Reusable Space Tug in Earth Vicinity in a European scenario, based on STRONG project objectives and constraints;
- ✓ No example exists with enough data for comparison, but the results can be verified with the existing roadmaps and literature;
- ✓ Considering STRONG project, the space tug has to be reusable (e.g. including a refuelling system), robotic, able to transfer a crew only as a payload, not able to perform a safe re-entry, equipped with an electrical propulsive system;
- ✓ The STRONG project scenario has been enlarged to the entire European scenario, adding also as a possible design solution multiple space tug assemblies;
- ✓ Even if no example exists with enough data to be compared to the presented case study, the data achieved are similar to the studies performed before and to what is present in literature in terms of costs, timing and choices.

Chapter 6

Conclusions

The study here presented is started from the definition of SoS to proceed analysing methodologies for its management, focusing on defining all the strategic plans required to reach SoS maturity in an on-going collaborative scenario and applying these methodologies to space exploration case studies (i.e. mission-oriented design activities). In particular, a SoS is an architecture composed by a certain number of individual systems that, maintaining their operational and managerial independence and interacting with the external social, economic and political scenario, are still able to accomplish functions not possible by any of them if operating alone. A common solution to achieve SoS management and to define its maturation plans is in the definition of technology roadmaps. Indeed, a technology roadmap is defined as a summary of science and technology plans, achieved after a current situation analysis aimed at identifying and selecting a certain number of strategic elements according to specific strategic plans and programmatic requirements.

In this context, a rational methodology has been developed with the main aim of supporting technology roadmaps definition and management in the context of a mission-oriented large-scale cooperative programme, reducing roadmap time-to-market. This methodology is also known as TRIS. TRIS is a rational, data-based and normative roadmapping methodology, based on Systems Engineering tools and processes, merged with Decision Analysis and Program Management tools and able to define and manage mission-oriented roadmaps in the context of an ongoing large-scale collaborative programme, describing SoSs. As a result, this methodology is able to start from the roadmap elements definition and characterization and proceeds up to the definition of a planning in terms of budget, schedule, missions and out-of-nominal scenarios analysis. In addition, exploiting TRIS is possible to propose a draft roadmap to experts for review, without having the need of supporting the draft roadmap definition with experts' opinions as is currently done. In this way, experts will have to review a roadmap obtained based on modular and structured elements obtained exploiting this specific methodology. The present thesis deals with the definition of a methodology for technology roadmap derivation and update that allows identifying an optimal solution within a similar scenario, decreasing roadmap time-to-market by proposing it to stakeholders through a semi-automatic process, substituting stakeholders' interactions when not strictly required.

This modularity itself is able to make the methodology flexible to different types of domains related to SoSs design activities, being applicable to many case studies easing its development and verification. Firstly, through examples in the European space exploration scenario, studies have allowed the sizing of every TRIS phase and results according to the SoS architecture features. Then, having defined and sized the main methodology features, two examples of complete application are proposed, verifying the proposed roadmap with literature or real case studies (such as IXV project): Hypersonic Space Transportation and Re-Entry Systems and Reusable Space Tugs in Earth Vicinity. To ease TRIS application in the different case studies, it has been implemented in an ad-hoc studied toolchain involving MS Office Excel® and Matlab®. This toolchain does not involve the first phase, i.e. the phase where the roadmap elements are defined, leaving this phase to the manual application of common System Design Processes based on Systems Engineering. It has to be said that in literature, commercial software toolchains exists that can implement this phase and that can be potentially combined with the TRIS toolchain both to speed up also the first element derivation phase and to ease the different element verification and update (e.g. increasing the traceability of the different results). An example of commercial software toolchain is the one proposed in (Stesina, 2017).

In addition, the proposed methodology is intended to be adapted itself to different type of users, which can be interested in looking specifically at a plan able to coordinate the efforts to enhance one or more roadmap element. This is true not only inside space exploration research field in which it is possible to define roadmaps for different types of Research Study Objectives, but also for every other research field where exists the need of coordinating a mission-oriented large-scale cooperative programme. Moreover even if TRIS has been developed over space exploration case studies cannot just be confined to it, as it is based on theories and tools applicable to a wild range of scenarios and this makes TRIS suitable to address the creation of roadmaps of other fields such as aeronautics.

In the methodology proposed for roadmap definition and update lays the innovative aspects of the work here presented. Indeed, differently from current space exploration roadmapping approaches, TRIS is a rational and semi-automatic support to the proposal of draft roadmaps related to SoS architectures and eventually manage strategic decisions for them. If data and feedbacks on a specific SoS architecture are available, it is possible to use TRIS for planning and prioritizing the technologies of this SoS even if related to different strategic targets. Exploiting data collection or in alternative statistical analysis, the methodology here presented can led to a semi-automatic data analysis process and roadmapping activity, that implements and rationalize some of the processes which are currently typical of many roadmapping activities and sometimes lack objectiveness. In addition, proposing a draft and already structured or standardized roadmap to stakeholders for review, it is possible to reduce the duration of the roadmapping activity itself, allowing the roadmap defined to be ready in lower time. Indeed, it has to be remembered the usual roadmapping activities in space exploration contexts usually last between 2 and 4 years.

The exploitation of Systems Engineering theories is at the same time TRIS strength and main limitation. On one side, the modularity achieved in the roadmap elements derivation and their hierarchical structure are useful features to ease roadmap derivation process, making it adaptable to any other kind of strategic roadmapping approach (e.g. technology-pull, mission-pull…). On the other side, these features are important requirements that have to be guaranteed. Another important requirement to be matched is the mission-oriented approach at least to derive the roadmap elements, here required to be compliant with usual System Design Processes in the proposed case studies field. Looking at missions to be performed and deriving products able to perform them it is useful to propose innovative missions types, but is a limit in finding new types of technologies. Indeed, the technologies derivation process is based on the definition of common technologies types, limiting for simplicity the technologies list to the specification of a single sizing feature. It has to be said that combining TRIZ with roadmapping approaches oriented to technologies innovation (such as “TRIZ-based Technology Roadmapping”) can overcome this limit. In addition, in the proposed examples, only technologies related to System Design Processes are proposed neglecting technologies coming from Product Realization Processes even if this part in TRIS is proposed. Considering these technologies is important for a planning definition, because are enabling technologies to achieve maturity in technologies related to System Design Processes that cannot be tested or verified without them. The method proposed in TRIS to include these technologies and the involvement of the right database or group of experts can be a solution to overcome this problem.

In a document-centric approach, the use of these tools is only related to the user accuracy and needs. Thanks to the rationale behind these tools and the possibility to apply to them a common language, a model-centric Systems Engineering, or Model Based Systems Engineering (MBSE) (Stesina, 2017), is emerging. The main advantages of this approach are in the capability to ease requirement management reducing mistakes, in the capability to produce and share models between stakeholders, in the possibility to automatically and consistently upgrade these models and in the possibility to apply a Model and Simulation (M&S) approach to reduce delays and over-costs related to defects in the final test session. On the market, software tools for MBSE are available both for the requirement management and for the functional and operational design process. For example, (Stesina, 2017) proposes a commercial software toolchain able to support a complete specification derivation process and the definition of models that can be then used to simulate the designed system for verification and validation purposes (Figure 119). The toolchain is here proposed to enhance Systems Engineering processes application exploiting the different commercial software tools capability of sharing data and models between them. In addition, it is also possible to ease the data update being them shared and fully traced, reducing the risk of loss of data and misunderstanding.

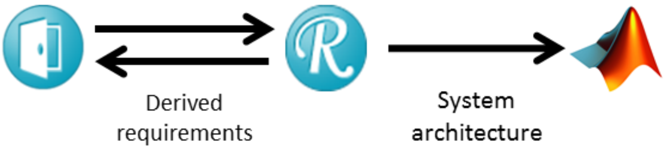


Figure 119: Toolchain structure

In particular, the proposed process applies in Rhapsody® Systems Modeling Language (SysML) (Friedenthal, 2008) modelling to drive Stakeholders and

Mission analyses, Functional Analysis and ConOps definition. Through this tool is possible to start an iterative requirements definition process supported by Dynamic Object Oriented Requirements System (DOORS®) as a database and a management tool directly link with Rhapsody®. Finally, the compatibility between these two tools and Matlab® or Simulink® allows the closing of the design loop ending in the simulation for the designed system being able to return from the simulation phase up to the requirements. Indeed, through Rhapsody® and DOORS® it is possible both to directly import/export data with Simulink® and to export data for other tools exploiting the interoperability standard Functional Mock-up Interface (FMI) for model exchange (Brusa, 2015).

The presence of these types of link with external tools can be exploited also for other applications. For example, the possibility to export Functions and Products Trees or Functions/Products Matrixes can be a support to TRIS, allowing the definition of a toolchain able to derive and update roadmaps. First, the application of a similar toolchain can ease the definition of the roadmap elements in an environment where it is easy to trace and verify them. Secondly, the possibility to exchange data from and to a toolchain implemented in an environment based on Matlab® can give inputs for other TRIS phases such as the Applicability Analysis.

References

Abe H. (2013). *The Innovation Support Technology (IST) approach: Integrating business modeling and roadmapping methods*. In: *Technology Roadmapping for Strategy and Innovation: Charting the Route to Success*. pp. 173–188.

Abe H., Ashiki T., Suzuki A., Jinno F. and Sakuma H. (2009). *Integrating business modeling and roadmapping methods - The Innovation Support Technology (IST) approach*. Technological Forecasting and Social Change. 76 (1). pp. 80–90.

van den Abeelen L. (2016). *Spaceplane HERMES: europe's dream of independent manned spaceflight*. Springer Praxis Books. [Online]. Springer International Publishing. Available from: https://books.google.it/books?id=vLadDQAAQBAJ.

Aizier B., Lizy-Destrez S., Seidner C., Chapurlat V., Prun D. and Wippler J.L. (2012). *xFFBD: towards a formal yet simple and complete functional modeling technique for system designers*. In: *INCOSE 2012, 22nd Annual International Council on Systems Engineering Symposium*. [Online]. 2012, Rome, Italy. Available from: https://hal-enac.archives-ouvertes.fr/hal-01022483.

Alcorn G., Scott S., Morrow G., Figueroa O. and Watkins M. (2009). *Risk management reporting*. *Goddard Technical Standard*. [Online]. Available from: GSFC-STD-0002.

American Space Foundation (2015). *The space report 2015: the authoritative guide to global space activity*. [Online]. Available from: www.SpaceFoundation.org.

Andrews J. (2012). *Spaceflight Secondary Payload System and SHERPA tug - A new business model forsecondary and hosted payloads*. In: *SSC12-V-6 ,26th Annual AIAA/USU Conference on Small Satellites*. 2012.

ASD-Eurospace (2012). *RT priorities 2012, Space R&T priorities*.

Battiston R. (2016). *Strategic vision document 2016-2025*. [Online]. Available from: https://www.asi.it/sites/default/files/attach/dettaglio/dvs-ing_web.pdf.

Bayer M. (1995). *Hermes: learning from our mistakes*. Space Policy. [Online]. 11 (3). pp. 171–180. Available from: http://www.sciencedirect.com/science/article/pii/0265964695000166.

Beeton D.A., Phaal R. and Probert D.R. (2013). *Exploratory roadmapping: capturing, structuring and presenting innovation insights*. In: *Technology Roadmapping for Strategy and Innovation: Charting the Route to Success*. pp. 225–240.

Behrens B. and Müller M. (2004). *Technologies for thermal protection systems applied on re-usable launcher*. In: *Acta Astronautica*. 2004, pp. 529–536.

Bennett T., Rowan J., Saluzzi A. and Langlois S. (2012). *Design, Development and Verification of the Intermediate eXperimental Vehicle Descent System*. In: 2012.

Bhattacharya A.B. and Lichtman J.M. (2016). *Solar planetary systems: stardust to terrestrial and extraterrestrial planetary sciences*. [Online]. CRC Press. Available from: https://books.google.it/books?id=EOCVDQAAQBAJ.

Bilbro J.W. (2006). *Systematic assessment of the program/project impacts of technological advancement and insertion. a white paper.*

Bott R. (2014). *Vega user's manual*. Igarss 2014. (4, Revision 0). pp. 1–5.

Brusa E., Ferretto D. and Cala A. (2015). *Integration of heterogeneous functional-vs-physical simulation within the industrial system design activity*. In: *2015 IEEE International Symposium on Systems Engineering (ISSE)*. [Online]. 2015, pp. 303–310. Available from: http://ieeexplore.ieee.org/document/7302774/.

Buffenoir F., Zeppa C., Pichon T. and Girard F. (2016). *Development and flight qualification of the C–SiC thermal protection systems for the IXV*. Acta Astronautica. [Online]. 124. pp. 85–89. Available from: http://www.sciencedirect.com/science/article/pii/S0094576516000576.

Burlton R. (2011). *BPM critical success factors, Lessons learned from successful BPM organizations. a white paper.*

Carvalho M.M., Fleury A. and Lopes A.P. (2013). *An overview of the literature on technology roadmapping (TRM): Contributions and trends*. Technological Forecasting and Social Change. [Online]. 80 (7). pp. 1418–1437. Available from: http://www.sciencedirect.com/science/article/pii/S0040162512002934.

Cazaux C., Watillon P., Durand G. and the ARD Team ESA/CNES (1995). *Atmospheric Re-entry Demonstrator (ARD): a flight experiment for technology qualification within the European Manned Space Transportation Programme (MSTP). European Space Agency, (Special Publication) ESA SP*. [Online]. 367 (ESA Bulletin N. 82) p.pp. 463–466. Available from: http://www.esa.int/esapub/bulletin/bullet82/cazau82.htm.

Chapman R.J. (2016). *A framework for examining the dimensions and characteristics of complexity inherent within rail megaprojects*. International Journal of Project Management. [Online]. 34 (6). pp. 937–956. Available from: http://www.sciencedirect.com/science/article/pii/S0263786316300187.

Charania A., Crocker A.M., Bradford J.E. and Olds J.R. (2001). *A method for strategic technology investment prioritization for advanced space transportation systems*. In: *Proceedings of the International Astronautical Congress (IAC)*. 2001.

Chavagnac C., Poincheval C., Iranzo-Greuz D., Kruger J. and Bouaziz L. (2006). *The future of European heavy-lift launchers over the next fifteen years*. In: *Proceedings of the International Astronautical Congress (IAC)*. [Online]. 2006. Available from: IAC-06-D2.2.02.

Chen P. (2002). *Entity-relationship modeling: historical events, future trends, and lessons learned*. In: *Software Pioneers*. [Online]. pp. 296–310. Available from: http://link.springer.com/10.1007/978-3-642-59412-0_17.

Chiesa S., Corpino S., Plucinski K., Stesina F. and Viola N. (2005). *VeLChYD - Very Low Cost Hypersonic Demonstrator for a Complete Orbital Reentry Mission*. In: *AIAA/CIRA 13th International Space Planes and Hypersonics Systems and Technologies Conference*. International Space Planes and Hypersonic Systems and Technologies Conferences. [Online]. American Institute of Aeronautics and Astronautics. Available from: https://doi.org/10.2514/6.2005-3345.

Clausen K.C., Hassan H., Verdant M., Couzin P., Huttin G., Brisson M., Sollazzo C. and Lebreton J.P. (2002). *The Huygens Probe system design*. *Space Science Reviews*. 104 (1–4) p.pp. 155–189.

Cole S.K. (2013). *Technology estimating: a process to determine the cost and schedule of space technology research and development*. NASA technical paper. [Online]. Available from: https://books.google.it/books?id=L8q1AQAACAAJ.

Committee on Human Spaceflight, Aeronautics and Space Engineering Board, Committee on National Statistics, Division on Earth and Physical

Sciences, Division of Behavioral and Social Sciences and National Research Council (2014). *Pathways to exploration: rationales and approaches for a US program of human space exploration*. [Online]. National Academies Press. Available from: https://books.google.it/books?id=PF7ZoAEACAAJ.

Copeland E.J., Holzer T.H., Eveleigh T.J. and Sarkani S. (2015). *The effects of system prototype demonstrations on weapon systems*. *Defense ARJ*. [Online]. 22 (1) p.pp. 106–134. Available from: http://dau.dodlive.mil/2015/01/02/the-effects-of-system-prototype-demonstrations-on-weapon-systems/.

Cresto Aleina S. (2011). *Veicoli transatmosferici: tipi, caratteristiche e approccio al progetto (Trans-atmospheric vehicles: categories, features and design approach)*. Politecnico di Torino.

Cresto Aleina S., Dentis M., Ferraris S., Maggiore P., Viola N. and Viscio M.A. (2015a). *Reusable space tug concept and mission*. In: *Proceedings of the International Astronautical Congress (IAC)*. [Online]. 2015, Jerusalem, Israel. Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-84991480410&partnerID=MN8TOARS.

Cresto Aleina S., Ferretto D., Stesina F. and Viola N. (2016a). *A model-based approach to the preliminary design of a space tug aimed at early requirement's verification*. In: *Proceedings of the International Astronautical Congress (IAC)*. 2016, Guadalajara, Mexico.

Cresto Aleina S., Fusaro R., Viola N., Longo J.M.A. and Saccoccia G. (2017a). *Technology roadmaps derivation methodology for European hypersonic and re-entry space transportation systems*. In: *21st AIAA International Space Planes and Hypersonics Technologies Conference, Hypersonics 2017*. 2017, Xiamen, China.

Cresto Aleina S., Fusaro R., Viola N., Rimani J., Longo J.M.A. and Saccoccia G. (2017b). *Comprehensive methodology for technology roadmaps generation and update for the European hypersonic and re-entry space transportation scenario*. In: *Proceedings of the International Astronautical Congress (IAC)*. [Online]. 2017, Adelaide, Australia. Available from: IAC-17.D2.IP.6.x38979.

Cresto Aleina S., Levrino L., Fusaro R. and Viola N. (2015b). *Effective methodologies to derive strategic decisions from ESA technology roadmaps*. In: *Proceedings of the International Astronautical Congress (IAC)*. [Online]. 2015, Jerusalem, Israel: International Astronautical Federation, IAF, pp. 9449–9459. Available from: http://porto.polito.it/2655937/.

Cresto Aleina S., Levrino L., Viola N., Fusaro R. and Saccoccia G. (2015c). *The importance of technology roadmaps for a successful future in space exploration*. In: *Proceedings of the 9th IAA Symposium on the Future of Space Exploration: Towards New Global Programmes*. [Online]. 2015, Turin, Italy. Available from: http://porto.polito.it/2657568/.

Cresto Aleina S. and Mozzetti Monterumici E. (2017c). *Optimized methodology for technology roadmaps definition and update for space systems in a System of Systems architecture*. In: *Proceedings of the International Astronautical Congress (IAC)*. [Online]. 2017, Adelaide, Australia. Available from: IAC-17.E2.1.4.x38694.

Cresto Aleina S., Viola N., Ferraris S. and Viscio M.A. (2015d). *Design of a reusable space tug*. In: *XXIII AIDAA Conference*. [Online]. 2015, p. 0. Available from: http://porto.polito.it/2644106/.

Cresto Aleina S., Viola N., Fusaro R., Longo J.M.A. and Saccoccia G. (2017d). *Basis for a methodology for roadmaps generation for hypersonic and re-entry space transportation systems*. Technological Forecasting and Social Change.

Cresto Aleina S., Viola N., Fusaro R. and Saccoccia G. (2017e). *Approach to technology prioritization in support of Moon initiatives in the framework of ESA exploration technology roadmaps*. Acta Astronautica. 139.

Cresto Aleina S., Viola N., Fusaro R. and Saccoccia G. (2016b). *Approach to technology prioritization in support of Moon initiatives in the framework of ESA exploration technology roadmaps*. In: *Proceedings of the International Astronautical Congress (IAC)*. 2016, Guadalajara, Mexico.

Cresto Aleina S., Viola N., Fusaro R. and Saccoccia G. (2016c). *Effective methodology to derive strategic decisions from ESA exploration technology roadmaps*. Acta Astronautica. [Online]. Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-84969811648&partnerID=MN8TOARS.

Cresto Aleina S., Viola N., Fusaro R. and Saccoccia G. (2017f). *Using the ESA exploration technology roadmaps in support of new mission concepts and technology prioritization*. In: *Proceedings of the 10th IAA Symposium on the Future of Space Exploration:Towards Space Village and Beyond*. 2017, Turin, Italy.

Cresto Aleina S., Viola N., Stesina F., Viscio M.A. and Ferraris S. (2016d). *Reusable space tug concept and mission*. Acta Astronautica. [Online]. Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-

84990981874&partnerID=MN8TOARS.

Dale Reed R. and Lister D. (1997). *Space-Station Rescue Vehicle*. In: *Wingless Flight, The lifting body story*. [Online]. Lexington, USA: The University Press of Kentucky, pp. 186–191. Available from: http://uknowledge.uky.edu/upk_history_of_science_technology_and_medicine/12/.

DeMaster-Smith L., Kimbrel S., Carpenter C., Overton S., Myers R. and King D. (2013). *Solar Electric Propulsion (SEP) benefits for near term space exploration*. In: The George Was (ed.). *The 33rd International Electric Propulsion Conference*. 2013, IEPC-2013-45.

Doericht V. (2013). *Strategic visioning – Future of business*. In: *Technology Roadmapping for Strategy and Innovation: Charting the Route to Success*. pp. 257–265.

Domb E. and Dettmer H.W. (1999). *Breakthrough Innovation In Conflict Resolution Marrying TRIZ and the Thinking Process*. Proceedings of the APICS Constraint Management Special Interest Group. [Online]. p. 11. Available from: http://goalsys.com/books/documents/TRIZPaper.pdf.

ECSS Secretariat (2014). *Space engineering: adoption notice of ISO 16290, Space systems - Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment*. Noordwijk, The Netherlands.

ECSS Secretariat (2009). *Space Project Management: project planning and implementation*. Noordwijk, The Netherlands.

ECSS Secretariat (2017). *Systems Engineering general requirements, ECSS-E-ST-10C Rev.1*. Noordwijk, The Netherlands.

EIRMA (1997). *Technology roadmapping: delivering business vision*. Working group reports. [Online]. EIRMA. Available from: https://books.google.it/books?id=9WCYGwAACAAJ.

ESA (2015a). *Exploring together: ESA space exploration strategy*. Noordwijk, The Netherlands.

ESA (2016). *Outcome of workshop on space exploration technologies and way forward, Annex 3*. Paris, France.

ESA (2015b). *Technologies for space exploration roadmaps*.

FAA (2016). *The annual compendium of space transportation: 2016*. [Online]. Available from:

https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2016_Compendium.pdf.

Fanmuy G., Goubault E., Krob D. and Stephan F. (2016). *Complex systems design and management*. In: *Proceedings of the 7th International Conference on Complex Systems Design & Management, CSD&M 2016*. [Online]. 2016, Paris, France: Springer, pp. 13–14. Available from: https://doi.org/10.1007/978-3-319-49103-5.

Farrokhzad B., Kern C. and de Vries M. (2013). *Innovation business plan at siemens: portfolio-based roadmapping to focus on promising innovation projects right from the beginning*. In: *Technology Roadmapping for Strategy and Innovation: Charting the Route to Success*. pp. 211–223.

Fenwick D., Daim T.U. and Gerdsri N. (2009). *Value Driven Technology Road Mapping (VTRM) process integrating decision making and marketing tools: case of Internet security technologies*. Technological Forecasting and Social Change. 76 (8). pp. 1055–1077.

Fiore E., Tamborrini P. and Barbero S. (2017). *Design for next connected appliances*.

Floyd C. (1997). *Managing technology for corporate success*. [Online]. Gower. Available from: https://books.google.it/books?id=fSvcNJZ8nT4C.

Flyvbjerg B. (2016). *The Oxford handbook of megaproject management*. The Oxford Handbook of Megaproject Management. (April). pp. 8–10.

Forczyk L.S. (2015). *Swiss Space Systems (S3)*. The Space Congress Proceedings.

Friedenthal S., Moore A. and Steiner R. (2008). *A practical guide to SysML*.

Fusaro R., Cresto Aleina S., Viola N., Longo J.M.A. and Saccoccia G. (2017). *Database on hypersonic transportation systems: a versatile support for the technology roadmap generation and conceptual design activities*. In: *21st AIAA International Space Planes and Hypersonics Technologies Conference, Hypersonics 2017*. 2017, Xiamen, China.

Galabova K. (2003). *Architecting a family of space tugs based on orbital transfer mission scenarios*. AIAA paper. [Online]. (September). pp. 1–224. Available from: http://strategic.mit.edu/docs/3_24_AIAA_2003_6368.pdf.

Garcia M.L. and Bray O.H. (1970). *Fundamentals of technology roadmapping*.

Gatti L. (2012). *ADR and OOSS: Thales AleniaSpace views*. In:

SWF/IfriConference. 2012, Brussels, Belgium.

Geschka H. and Hahnenwald H. (2013). *Scenario-based exploratory technology roadmaps - A method for the exploration of technical trends*. In: *Technology Roadmapping for Strategy and Innovation: Charting the Route to Success*. pp. 123–136.

Geschka H. and Schauffele J. (2005). *Explorative technologie roadmaps - Eine methodik zur erkundung technologischer entwicklungslinien und potenziale*. Technologie-Roadmapping. [Online]. pp. 165–188. Available from: http://www.springerlink.com/index/M246441112V0684G.pdf.

Gogolla M., Hamann L., Hilken F. and Sedlmeier M. (2015). *Modeling behavior with interaction diagrams in a UML and OCL tool*. In: *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. 2015, pp. 31–58.

Gollub C. and de Vivie-Riedle R. (2009). *Multi-objective genetic algorithm optimization of 2D- and 3D-Pareto fronts for vibrational quantum processes*. New Journal of Physics. 11.

Graham T. and Allan W. (2006). *CIMA exam practice kit, Management accounting business strategy*. CIMA Exam Practice Kit. [Online]. Elsevier Science. Available from: https://books.google.it/books?id=UntLssYm5m0C.

Grover D., Jacobs S., Abbasi V., Cree D., Daae M., Hay J., He W., Huang X., Jun Z., Kearney S., Kuwahara T., Lenzi F., Mirahmetoglu H., Morley S., Otani M., Pastena M., Pinni M., Schwartz J., Shala K. and Weeden C. (2008). *Development of on-orbit servicing concepts, Technology option and roadmap (Part I) - Commercial aspects*. Journal of the British Interplanetary Society. 61. pp. 203–212.

Guerra L. (2008). *The project lifecycle module. Course of 'Space Systems Engineering'.*

Hannigan R.J. (1994). *Spaceflight in the era of aero-space planes*. [Online]. Krieger. Available from: https://books.google.it/books?id=kZRTAAAAMAAJ.

Harrison E.F. and Pritchard E.B. (1971). *Use of space tug to increase payload capability of Space Shuttle*. Hampton, VA, USA.

Haya Ramos R., Blanco G., Angelini R. and Mancuso S. (2015). *Flight predictions for the IXV mission*. Proceedings of the 8th European Symposium on Aerothermodynamics for Space Vehicles. [Online]. Available from: Paper No 91958.

Héder M. (2017). *From NASA to EU: the evolution of the TRL scale in public sector innovation*. Innovation Journal. 22 (2).

Hooks I. (2004). *Managing requirements for a System of Systems*. Journal of Defence Software Engineering. [Online]. (August). pp. 4–7. Available from: http://stsc.hill.af.mil/crosstalk/.

Hufenbach B., Laurini K.C., Satoh N., Martinez R., Hill J., Landgraf M. and Bergamasco A. (2015). *International missions to lunar vicinity and surface - Near-term mission scenario of the Global space Exploration Roadmap*. Proceedings of the International Astronautical Congress (IAC).

Iafrati A., La Gala F., Miozzi M. and Di Vita G. (2012). *Water impact experimentsona scaled IXV model*. In: *European Space Agency, (Special Publication) ESA SP*. 2012.

IEA (2014). *Energy technology roadmaps, A guide to development and implementation. IEA Publications*.

INCOSE (2015). *INCOSE Systems Engineering handbook: a guide for system life cycle processes and activities*. 4th Ed. Wiley.

ISECG (2018). *The Global Exploration Roadmap*. [Online]. Available from: http://www.globalspaceexploration.org.

ISECG (2013). *The Global Exploration Roadmap*. [Online]. Available from: http://www.globalspaceexploration.org.

Jakhu R.S., Sgobba T. and Dempsey P.S. (2011). *The need for an integrated regulatory regime for aviation and space: ICAO for space?* [Online]. Available from: http://dx.doi.org/10.1007/978-3-7091-0718-8.

Jefferies S.A. and Merrill R.G. (2015). *Viability of a reusable in-space transportation systems*. In: *AIAA SPACE 2015 Conference and Exposition, AIAA SPACE Forum*. 2015, AIAA 2015-4580.

Kanama D. (2010). *A Japanese experience of a mission-oriented multi-methodology technology foresight process: an empirical trial of a new technology foresight process by integration of the Delphi method and scenario writing*. International Journal of Technology Intelligence and Planning. [Online]. 6 (3). p. 253. Available from: http://www.inderscience.com/link.php?id=35778.

Kanama D. (2013a). *Development of technology foresight: integration of* *technology roadmapping and the delphi method*. In: *Technology Roadmapping for Strategy and Innovation: Charting the Route to Success*. pp. 151–171.

Kanama D. (2013b). *Technology roadmapping for strategy and innovation*. [Online]. Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-84938509928&partnerID=tZOtx3y1.

Kerr C.I. V., Phaal R. and Probert D.R. (2013). *Roadmapping as a responsive mode to government policy: a goal-orientated approach to realising a vision*. In: *Technology Roadmapping for Strategy and Innovation: Charting the Route to Success*. pp. 67–87.

Kian Manaesh Rad E. and Sun M. (2014). *Taxonomy of project complexity indicators in energy megaprojects*.

Kleine O. and Braun A. (2014). *Documentation of the roadmapping methodology and overview over the roadmapping documents, Deliverable D1.1.1*.

Kossiakoff A., Sweet W.N., Seymour S.J. and Biemer S.M. (2011). *Systems Engineering principles and practice*. [Online]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/20576311%5Cnhttp://books.google.com/books?id=MRZoj0yAm9oC&pgis=1.

Kuczera H., Krammer P. and Sacher P.W. (1991). *Sänger and the German hypersonic technology programme*. In: *Proceedings of the International Astronautical Congress (IAC)*. [Online]. 1991, Montreal, USA. Available from: IAF-91-198.

Kuczera H., Sacher P.W. and Dujarric C.H. (1996). *FESTIP system study - An overview*. In: *Space Plane and Hypersonic Systems and Technology Conference*. International Space Planes and Hypersonic Systems and Technologies Conferences. [Online]. American Institute of Aeronautics and Astronautics. Available from: https://doi.org/10.2514/6.1996-6004.

Kujawski E. (2013). *Analysis and critique of the System Readiness Level*.

Larson W.J. and Pranke L.K. (2000). *Human spaceflight: mission analysis and design*.

Larson W.J. and Wertz J.R. (2005). *Space Mission Analysis and Design*. [Online]. Available from: http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=7369177.

LEAG (2016). *The lunar exploration roadmap: exploring the Moon in the 21st* *century: themes, goals, objectives, investigations and priorities*. [Online]. Available from: https://www.lpi.usra.edu/leag/LER-2016.pdf.

Longo J.M.A. (2009). *Lifting re-entry: present results and future challenges of the DLR SHEFEX program*. 16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference. [Online]. Available from: AIAA-Paper 2009-7226.

Lovera F. (2016). *System budget per sistemi spaziali (System budgets for space systems)*. Politecnico di Torino.

Luzeaux D., Ruault J.R.Ã. and Wippler J.L. (2013). *Large-scale complex system and Systems of Systems*. ISTE. [Online]. Wiley. Available from: https://books.google.it/books?id=hb-7Nndexr0C.

Maier M.W. (1998). *Architecting principles for Systems of Systems*. Systems Engineering. [Online]. 1 (4). pp. 267–284. Available from: http://dx.doi.org/10.1002/(SICI)1520-6858(1998)1:4%3C267::AID-SYS3%3E3.0.CO;2-D.

Mankins J.C. (2009). *Technology readiness assessments: a retrospective*. Acta Astronautica. [Online]. 65 (9). pp. 1216–1223. Available from: http://www.sciencedirect.com/science/article/pii/S0094576509002008.

Manzo V., Yambrick L. and Bunn M.E. (2007). *Toward a theory of spacepower: selected essays*. N. D. University (ed.).

Mason J. (1972). *Space tug performance optimization*. Journal of Spacecraft and Rockets. 9 (7). pp. 491–492.

Massobrio F. and Rufolo G. (2016). *Space Rider, The reusable orbital/re-entry vehicle for Europe*. In: *2nd CESMA Hypersonic flight Symposium*. 2016, Rome, Italy, Italy.

McNamee P. and Celona J. (2001). *Decision Analysis for the professional*. [Online]. SmartOrg. Available from: https://books.google.it/books?id=JXL8PQAACAAJ.

Messidoro P. (2013). *Strategic roadmaps for exploration and science technologies in Thales Alenia Space in view of H2020*. In: *Horizon 2020: a challenge and opportunity for Aerospace Sector - From Leading Players to SMEs*. 2013, Turin, Italy.

Moehrle M.G. (2013). *TRIZ-based technology roadmapping*. In: *Technology Roadmapping for Strategy and Innovation: Charting the Route to Success*. pp. 137–150.

Moehrle M.G. (2005). *What is TRIZ? From conceptual basics to a framework for research*. Creativity and Innovation Management. 14 (1). pp. 3–13.

Moehrle M.G., Isenmann R. and Phaal R. (2013). *Technology roadmapping for strategy and innovation: charting the route to success*.

NACCHO (2010). *Guide to prioritization techniques*. [Online]. Available from: http://www.naccho.org/uploads/downloadable-resources/Gudie-to-Prioritization-Techniques.pdf.

NASA (2014). *A new era in spaceflight. Commercial Orbital Transportation Services*. [Online]. NASA/SP-20. Available from: https://www.nasa.gov/sites/default/files/files/SP-2014-617.pdf.

NASA (2015). *Introduction, crosscutting technologies and index, NASA technology roadmaps*.

NASA (2012). *NASA space technology roadmaps and priorities: restoring NASA's technological edge and paving the way for a new era in space*. Steering Committee for NASA Technology Roadmaps & National Research Council of the National Academies (eds.). [Online]. National Academies Press. Available from: https://books.google.it/books?id=-SFBDO6PKmUC.

NASA (2010). *On-orbit satellite servicing study*. Project Report - Goddard Space Flight Center. (October). p. 190.

NASA (2005). *Program and Project Management processes and requirements*. Washington DC, USA.

NASA (2017). *Systems Engineering handbook*. Washington DC, USA.

NASA JSC (2009). *Dra 5.0*.

Nimmo G. (2013). *Technology roadmapping on the industry level: experiences from Canada*. In: *Technology Roadmapping for Strategy and Innovation: Charting the Route to Success*. pp. 47–65.

Obersteiner M. (2001). *Per PHOENIX and ASTRA*. Aircraft Engineering and Aerospace Technology. 73.

Oda M. (2012). *On-orbit satellite servicing 'Status and strategy of Japan'*. In: *The 2nd International Workshop on On-Orbit Satellite Servicing*. 2012, Greenbelt, Md.

Patrignani N. and Kavathatzopoulos I. (2017). *On the difficult task of teaching computer ethics to engineers*.

Phaal R., Farrukh C.J.P. and Probert D.R. (2004). *Technology roadmapping - A planning framework for evolution and revolution*. Technological Forecasting and Social Change. 71 (1–2). pp. 5–26.

Pritchard C. (2006). *Visualizing Project Management: models and frameworks for mastering complex systems*. Project Management Journal. [Online]. 37 (3). p. 62. Available from: http://search.ebscohost.com/login.aspx?direct=true&db=bth&AN=21463507&site=ehost-live.

Puettmann N. (2003). *Research and development of re-entry technologies in Germany after TETRA/X-38*. In: *Proceedings of the International Astronautical Congress (IAC)*. International Astronautical Congress (IAF). [Online]. American Institute of Aeronautics and Astronautics. Available from: https://doi.org/10.2514/6.IAC-03-V.3.09.

Pullan D., Sims M.R., Wright I.P., Pillinger C.T. and Trautner R. (2004). *Beagle 2: The exobiological lander of Mars express*. *European Space Agency, (Special Publication) ESA SP*. (1240) p.pp. 165–204.

Richards M., Springmann P. and Mcvey M. (2005). *Assessing the challenges to a geosynchronous space tug system*. Proceedings of the SPIE. 5799. pp. 135–145.

Russel C.T., Raymond C.A., Fraschetti T.C., Rayman M.D., Polanskey C.A., Schimmels K.A. and Joy S.P. (2005). *Dawn mission and operations*. Proceedings of the International Astronomical Union. 1 (S229). pp. 97–119.

Russo G. and Capuano A. (2002). *The PRORA-USV program*. *European Space Agency, (Special Publication) ESA SP*. 487 p.pp. 37–48.

Saccoccia G., Ferracina L., Wormnes K., Bergamasco A., Viola N., Cresto Aleina S. and Fusaro R. (2015). *Use of ESA exploration technology roadmaps in support of Moon initiatives and technology prioritisation*. *Moon 2020-2030 Symposium*. presentati.

Saccoccia G., de Groot R. and Hufenbach B. (2014). *ESA coordination activities on space exploration: technology roadmaps*. In: *International Space Exploration Forum*. 2014, Washington DC, USA.

Saccoccia G., Schrogl K.U., Duvaux-Bechon I., Peter N., de Groot R., Gardini B. and Naja G. (2012). *Coordinated ESA initiatives in technologies for space exploration*. In: *Proceedings of the Global Space Exploration Conference (GLEX)*. [Online]. 2012, Washington DC, USA. Available from: http://iafastro.directory/iac/paper/id/12782/summary/.

Saccoccia G., Wormnes K., Landgraf M., Villace V.F., Viola N., Cresto Aleina S. and Fusaro R. (2017). *European approach for space exploration technology procurement: methodologies and tools*. In: *Proceedings of the International Astronautical Congress (IAC)*. [Online]. 2017, Adelaide, Australia. Available from: IAC-17.D3.4.3.x38954.

Sage A.P. and Cuppan C.D. (2001). *On the systems engineering and management of Systems of Systems and federations of systems*. Information, Knowledge, Systems Management. [Online]. 2 (4). pp. 325–345. Available from: http://iospress.metapress.com/content/WX6B5WFT80K8P9A2.

Sammut-Bonnici T. and Galea D. (2015). *PEST analysis*. In: *Wiley Encyclopedia of Management*. [Online]. pp. 1–1. Available from: http://doi.wiley.com/10.1002/9781118785317.weom120113.

Sauser B.J., Long M., Forbes E. and McGrory S.E. (2009). *Defining an Integration Readiness Level for Defense Acquisition*. INCOSE International Symposium. [Online]. 19 (1). pp. 352–367. Available from: http://dx.doi.org/10.1002/j.2334-5837.2009.tb00953.x.

Scholes K. (1998). *Stakeholder mapping: a practical tool for managers*. In: V. Ambosini, G. Johnson, & K. Scholes (eds.). *Exploring Techniques of Analysis and Evaluation in Strategic Management*. Hemel Hempstead, Prentice Hall.

Schuh G., Orilski S., Schmelter K. and Klappert S. (2009). *Technologie-roadmapping: erfolgreiche umsetzung in der industriellen praxis*. ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb. [Online]. 104 (4). pp. 291–299. Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-66749156465&partnerID=tZOtx3y1.

Schuh G., Wemhöner H. and Orilski S. (2013). *Technological overall concepts for future-oriented roadmapping*. In: *Technology Roadmapping for Strategy and Innovation: Charting the Route to Success*. pp. 107–121.

Schweickart R.L., Lu E.T., Hut P. and Chapman C.R. (2003). *The asteroid tugboat*. Scientific American. 289 (5). pp. 54–61.

Sevastiyanov N. and Bryukhanov N. (2006). *Clipper reusable space transport system*. In: *Proceedings of the International Astronautical Congress (IAC)*. 2006.

Steele L.W. (1989). *Managing technology: the strategic view*. McGraw-Hill engineering and technology management series. [Online]. McGraw-Hill. Available from: https://books.google.it/books?id=-hVPAAAAMAAJ.

Steffes S., Theil S., Samaan M. and Michael C. (2012). *Flight results from the SHEFEX2 hybrid navigation system experiment. AIAA Guidance, Navigation and Control Conference.*

Stesina F., Cresto Aleina S., Ferretto D. and Viola N. (2017). *Design process of a reusable space tug based on a Model Based Approach. WSEAS Transactions on Computers*. 16, Art. # p.pp. 133–145.

Trella M. (1989). *Introduction to the hypersonic phenomena of HERMES*. In: J. J. Bertin, R. Glowinski, & J. Periaux (eds.). *Hypersonics - Defining the Hypersonic Environment*. [Online]. pp. 67–91. Available from: http://www.springer.com/it/book/9781468491890.

Tumino G., Angelino E., Leleu F., Plotard P. and Angelini R. (2008). *The IXV Project, The ESA re-entry system and technologies demonstrator paving the way to European autonomous space transportation and exploration endeavours*. In: *Proceedings of the International Astronautical Congress (IAC)*. [Online]. 2008. Available from: http://iafastro.directory/iac/archive/browse/IAC-08/D2/6/895/.

Tumino G., Mancuso S., Gallego J.M., Dussy S., Preaud J.P., Di Vita G. and Brunner P. (2016). *The IXV experience, From the mission conception to the flight results*. Acta Astronautica. 124. pp. 2–17.

UNIDO (2005). *Technology foresight manual organization and methods*.

US DoD (2017). *Acquisition System*. [Online]. Available from: https://www.dau.mil/guidebooks/Shared Documents HTML/DoDI 5000.02.aspx.

US Government (2001). *Systems Engineering fundamentals*. [Online]. Available from: http://www.dtic.mil/docs/citations/ADA387507.

Varvill R. and Bond A. (2004). *The SKYLON spaceplane*. Journal of the British Interplanetary Society. 57. pp. 22–32.

Viola N., Corpino S., Fioriti M. and Stesina F. (2012). *Functional Analysis in Systems Engineering: methodology and applications*. In: *Systems Engineering - Practice and Theory (Prof. Dr. Boris Cogan)*. RIJEKA:InTech, pp. 71–96.

Viola N., Cresto Aleina S., Fusaro R., Saccoccia G. and Longo J.M.A. (2016). *Technology roadmaps preparation for European hypersonic and re-entry space transportation systems*. In: *Proceedings of the International Astronautical Congress (IAC)*. 2016.

Viscio M.A. (2014). *Space exploration systems, Strategies and solutions*. [Online]. Politecnico di Torino. Available from: http://porto.polito.it/2538894/.

Viscio M.A., Gargioli E., Hoffman J.A., Maggiore P., Messidoro A. and Viola N. (2014a). *A methodology for innovative technologies roadmaps assessment to support strategic decisions for future space exploration*. Acta Astronautica. 94 (2). pp. 813–833.

Viscio M.A., Gargioli E., Hoffman J.A., Maggiore P., Messidoro A. and Viola N. (2013a). *A methodology to support strategic decisions in future human space exploration: From scenario definition to building blocks assessment*. Acta Astronautica. 91. pp. 198–217.

Viscio M.A., Gargioli E., Hoffman J.A., Maggiore P., Messidoro A. and Viola N. (2012). *Future space exploration: from reference scenario definition to key technologies roadmaps*. In: *Proceedings of the International Astronautical Congress (IAC)*. 2012.

Viscio M.A., Viola N., Corpino S., Stesina F., Circi C., Fineschi S. and Fumenti F. (2013b). *Interplanetary CubeSats mission to Earth-Sun libration point for space weather evaluations*. Proceedings of the International Astronautical Congress (IAC). [Online]. 2. pp. 1324–1332. Available from: http://www.engineeringvillage.com/blog/document.url?mid=cpx_4d266e4c147b1a078f6M527f10178163125&database=cpx.

Viscio M.A., Viola N., Corpino S., Stesina F., Fineschi S., Fumenti F. and Circi C. (2014b). *Interplanetary CubeSats system for space weather evaluations and technology demonstration*. Acta Astronautica. 104 (2). pp. 516–525.

Viscio M.A., Viola N. and Gargioli E. (2013c). *A space tug for Earth satellites servicing*. In: *Italian Association of Aeronautics and Astronautics XXII Conference*. 2013, Naples, Italy.

Viscio M.A., Viola N., Gargioli E. and Vallerani E. (2013d). *Conceptual design of a habitation module for a deep space exploration mission*. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 227 (9). pp. 1389–1411.

Whipp R. (1991). *Managing technological changes, Opportunities and pitfalls*.

Wilde D. and Walther S. (2001). *Inflatable Re-entry and Descent Technology (IRDT) - Further developments. Proceedings of the 2nd International Symposium of Atmospheric Re-entry Vehicles and Systems*. [Online].

Available from: http://www.dlr.de/rb/Portaldata/38/Resources/dokumente/GSOC_dokumente/RB-RFT/arcachon_paper.pdf.

Willyard C.H. and McClees C.W. (1987). *Motorola's technology roadmap process*. Research Management. [Online]. 30 (5). pp. 13–19. Available from: https://doi.org/10.1080/00345334.1987.11757057.

XCOR Aerospace (2012). *XCOR Lynx payload user's guide*. [Online]. Available from: version 3b.