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TECHNOLOGY ROADMAPS FOR THE DEVELOPMENT OF FUTURE HIGH-SPEED TRANSPORTATION SYSTEMS

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Abstract

This paper describes the upgrade and application of Technology Roadmapping Strategy (TRIS) methodology to propose an incremental path (i.e., a technology roadmap) towards the increase of Technology Readiness Level (TRL) of STRATOFLY key-enabling technologies to meet the project's goal (TRL 6 in 2035). The paper discusses several improvements introduced within the roadmapping methodology in order to deal with future high-speed transportation systems. In particular, basing on Space Shuttle cost data, a general framework to assess the cost of TRL Transits for hypersonic technologies is proposed. In addition, a detailed analysis of future activities to be performed to pursue hypersonic technologies is included, with special emphasis on the importance of highly-integrated flight demonstrators at high TRL level in relation to involved stakeholders' impact and needs.

Keywords: technology roadmapping, STRATOFLY, Life Cycle Costs, high-speed transportation systems

1. Introduction

The development of technologies to enable future high-speed transportation systems has been the focus of several research activities co-funded by the European Commission (EC) since the mid-2000s, involving the European Space Agency (ESA) along with a number of partners from industry and universities. In this context, with the aim to reduce to about 2 to 4 hours the travelling time on antipodal routes (e.g. Brussels to Sidney), LAPCAT I/II projects [1], [2] studied advanced airbreathing propulsion concepts to reach hypersonic flight speeds (from Mach 3 to 8). In particular, several vehicle architectures were preliminary assessed in the framework of LAPCAT I, including a Mach 5 cruiser called LAPCAT A2 and characterized by a pre-cooled turboramjet and a Mach 8 scramjet-based vehicle named LAPCAT MR2.4 [3] (Figure 1). The latter were selected for further detailed evaluation during LAPCAT II project. In the meanwhile, ATLLAS I/II projects [4], [5] analyzed lightweight advanced materials able to withstand ultra-high temperatures and heat fluxes encountered during hypersonic flight, while HEXAFLY and HEXAFLY-Int projects [6], [7] studied the experimental flight testing of high-speed technologies through the preliminary design of a high-speed technology demonstrator. Moreover, FAST 20XX [8][9] proposed two suborbital concepts characterized by increasing technology complexity and hence projected to enter into service into two separate timelines, i.e. the air-launched ALPHA with hybrid rocket motor and the all-rocket powered Two-Stage to Orbit (TSTO) SpaceLiner. Eventually, it is also worth mentioning the HIKARI project [10], a joint effort between Europe and Japan which proposed a preliminary market analysis and a technology roadmap to support the development of a high-speed air transport vehicle, including the maturing process, ground and flight testing requirements.

Basing on the heritage of the afore-mentioned European activities in the framework of future high-speed transportation systems, the H2020 STRATOFLY (Stratospheric Flying Opportunities for High-Speed Propulsive Concepts) [11]–[13] started in 2018 and it is now at the finalization stage. STRATOFLY aims at assessing the potential of a high-speed transport vehicle to reach Technology Readiness Level (TRL) 6 by 2035 with respect to key technological, societal and economical aspects. Starting from the MR2.4 waverider vehicle (Figure 1, left) equipped with six Air Turbo Rockets (ATRs) and a Dual Mode Ramjet (DMR) studied during LAPCAT II project, STRATOFLY proposes the MR3 vehicle (Figure 1, right) with the same propulsive system and external configuration but addressing more in detail complex issues such as thermal and structural integrity, low-emission combined propulsion cycles and subsystems design and integration, including smart energy management. In addition, the project entails the environmental sustainability and the climate impact of the integrated vehicle as well as its economic viability.

Figure 1 LAPCAT MR2.4 [3] *(left) and STRATOFLY MR3 (right) cruiser concepts*

In line with STRATOFLY's objective to assess the potential to reach TRL 6 by 2035 for hypersonic technologies, the present paper aims at suggesting a technology roadmap towards the maturation of some key hypersonic technologies studied within the project. In particular, the paper applies the methodology and tool developed at Politecnico di Torino called Technology RoadmappIng Strategy (TRIS) to support the generation and update of technology roadmaps, proposing an incremental path towards the increase of the readiness level of STRATOFLY key enabling technologies. In particular, Section 2 provides a general overview of TRIS, recalling the main steps of the methodology. Two main innovative aspects are introduced in this section: a new estimation of CaC for each TRL transit and a new estimation of time request for each TRL transit, specifically tailored for hypersonic transportation. Section 3 describes the application to STRATOFLY, applying the improvements introduced in the overall technology roadmapping approach in order to deal with the case study. Eventually, Section 4 draws main conclusions and discusses envisaged future works.

2. TRIS Methodology Overview

In the last decades, an increased competition brought technology and innovation management to the center of decision-making processes and, in this context, technology roadmaps became a fundamental tool in understanding the relationship between available technological expertise and objectives to reach. In this context, Politecnico di Torino proposed a rational and logical methodology (TRIS) based on the combination of common Systems Engineering tools and processes and able to generate and update technology roadmaps for different case studies in the aerospace domain [14]–[16].

As treated in TRIS, a technology roadmap is the result of complex and strictly interwoven activities aiming at identifying and selecting technologies, missions, capabilities and systems to eventually support strategic decisions. Therefore, in a rational and structured way a technology roadmap expresses the interrelations between the following four elements, also referred to as "pillars":

1) Operational Capability (OC), defined as a high-level function responding to a mission statement, e.g., the capability to perform antipodal flights at Mach 8 for STRATOFLY;

2) Technology Domain (TD), including "knowhow relevant to a technical area" [17] and collecting a set of technologies to accomplish one or more OCs, for example Propulsion, Structures and Mechanisms, and Thermal TDs;

3) Building Block (BB), defined as a physical element that may include several technologies, combined together to achieve certain functions (OCs), e.g., a technology flight demonstrator;

4) Mission Concept (MC), defined through a mission statement and made up of BBs, in order to implement several OCs and make use of certain technologies, e.g., the flight mission performed by the demonstrator.

Figure 2 shows the flowchart of TRIS methodology. The overall approach starts with a Stakeholders' Analysis identifying all the entities that might be involved in the roadmapping process and specifying their role(s) and impact on the final goal. Then, the methodology proceeds defining the lists of elements (i.e., MCs, OCs, BBs and technologies) relevant to the case study along with the links between them. Once the lists of elements are collected, a prioritization process is applied to the list of technologies, which is ordered according to proper prioritization criteria, mirroring Stakeholders' needs. To support this process, a sensitivity analysis can also be performed to evaluate the impact of each stakeholder and/or criterion on the final ranked list of technologies. Eventually, the ranked list of technologies and the list of mission concepts shall be matched together to generate the incremental path to mature each technology. In particular, a time planning for technologies' development is suggested along with a preliminary estimation of the costs required to perform each TRL transit. At this point, a first technology roadmap is drafted and it is ready to be analyzed and further refined.

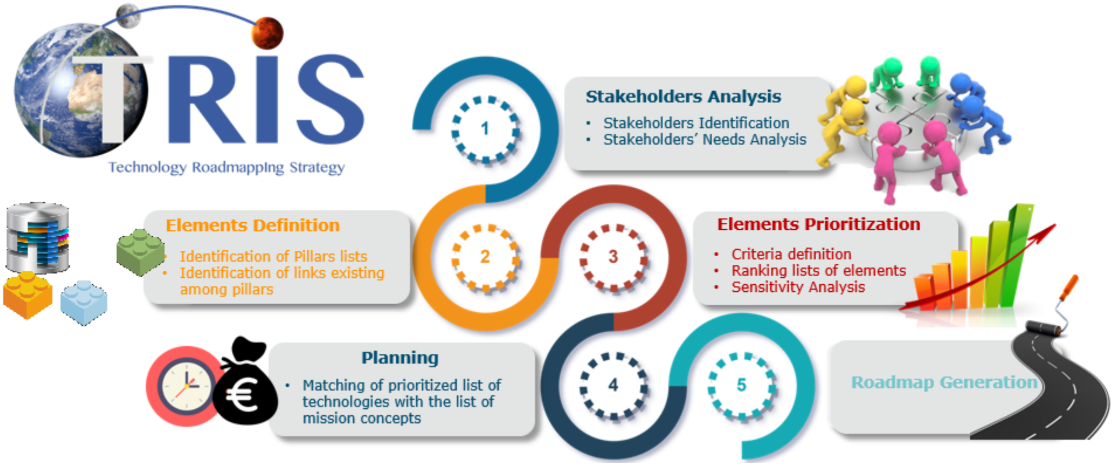


Figure 2 Flowchart of TRIS methodology

In the framework of previous roadmapping activities, Politecnico di Torino exploited TRIS methodology to propose technology roadmaps for Space Exploration systems [18] and hypersonic and re-entry space transportation systems [14][19]. For all this wide set of case studies, TRIS can be used to derive, track, and manage basic roadmap elements and to optimize their relationships in a decision-making process. In particular, as described in [14], relationships between technology maturation (i.e. TRL), program schedule (or time distribution) and Cost at Completion (CaC) are crucial . It is worth mentioning that CaC is the cost to be sustained to perform technology development up to TRL 9. Results from previous analyses on costs and time distributions are shown in Figure 3 [14], where on the left it is reported the CaC fraction required to perform each TRL transit for a hypersonic and re-entry space transportation system, while on the right the time fraction for each TRL transit applicable to a space exploration system. It is specified that the time distribution shown in Figure 3 has been also applied to hypersonic and re-entry space transportation systems in [14]. Two main innovative aspects have been introduced within this paper to handle STRATOFLY case study: the estimation of CaC for each TRL transit and time request for each TRL transit. As far as costs distribution is concerned, it has been revised in this work thanks to a thorough analysis of available Space Shuttle DDTE (Design Development, Test and Evaluation) cost data from [20]. The new costs breakdown, reported in Figure 4 (left), is substantially in line with the already available breakdown shown in Figure 3 (left) from previous studies. A similar analysis has been performed to obtain a time distribution on TRL Transits specifically tailored for hypersonic transportation systems using available time data from FESTIP and Sänger [21], [22]. Resulting time breakdown is provided in Figure 4 (right).

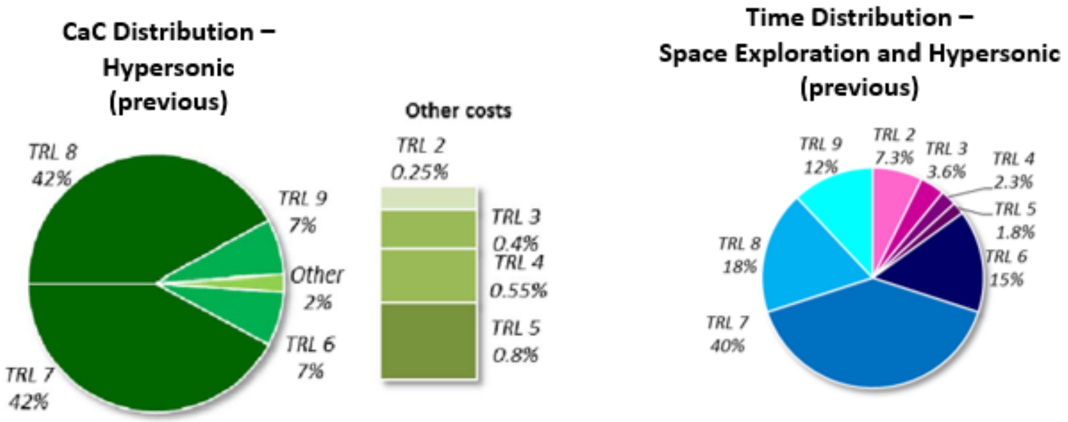


Figure 3 Previous CaC distribution for each TRL Transit - Hypersonic and Re-entry Space Transportation Systems (left) and time distribution for each TRL Transit – Space Exploration Systems (right)

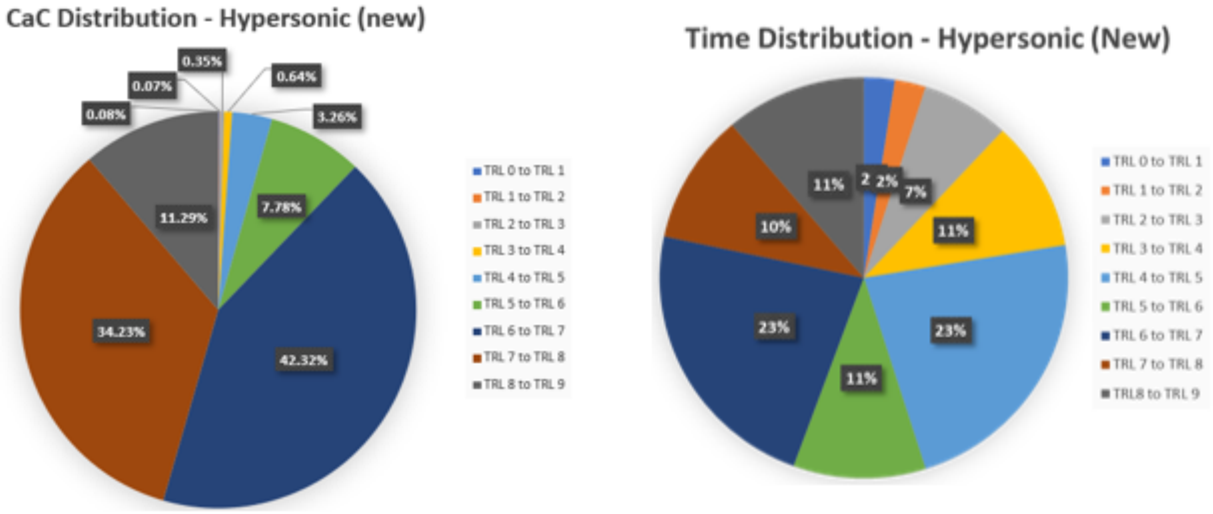


Figure 4 Newly derived CaC distribution on TRL transits using Space Shuttle data (left) and time distribution form FESTIP and Sänger data applicable to hypersonic transportation systems

As a result of previous analyses, TRIS methodology depicted in Figure 2 has been proven to be flexible enough to support roadmapping exercises for different case studies. Nevertheless, depending on the specific application treated, dedicated analyses shall be performed in order to derive proper lists of elements and links between elements exploiting available expertise or dedicated databases (Step 2 of the methodology). The lack of available data (e.g., list of technologies to be considered, TRL of each technology, CaC, etc.) could dramatically increase the effort required to propose a technology roadmap and the complexity of the overall process.

These challenges have been encountered also during the roadmapping activities aimed at proposing a technology roadmap for future hypersonic transportation systems like STRATOFLY MR3 described in this paper. In particular, the lack of a detailed database containing lists of technologies for each TD and of MCs imposed the definition of elements and elements' links from scratch. In addition, an assessment of the starting TRL of each technology was not available so that a preliminary estimation was necessary. In account of this, considering the role of propulsive technologies as key enablers of future hypersonic transportation systems, this paper proposes a preliminary technology roadmap focusing on propulsion system technologies. The goal is to verify the applicability of TRIS methodology to STRATOFLY MR3 throughout all the steps shown in Figure 2, assessing the modifications required to deal with the new case study, in order to possibly speed up the process for the remaining TDs in the future. Furthermore, considering the importance of flight demonstrators in the verification of hypersonic technologies, great effort has been posed in suggesting a proper set of demo mission to be performed in order to increase technology maturity. In this sense, the original planning routine (Step 4 in Figure 2) [19] has been revised in order to suggest a specific demo mission at the "best" time in the technology development, i.e. when all the technologies linked to that MC effectively reached the MC enabling TRL.

3. Application of TRIS Methodology to STRATOFLY

3.1 Stakeholders' Analysis

After selecting Propulsion as the crucial TD to focus the roadmapping exercise for STRATOFLY, a Stakeholders' Analysis has been performed with the aim to assess the main actors involved in vehicle development. In particular, as a preliminary assumption, the EC has been considered as unique stakeholder in the European hypersonic program, considering its role of funding institution in the European framework. In a further and more detailed analysis, the role and impact of research centers, universities, industries and airlines shall also be taken into account to provide a complete spectrum of the players involved. Imagining the EC as the only stakeholder, the following criteria were defined to rank the list of propulsive technologies. Please, notice that the final ranking of technologies will be impacted by the order in which they will be used. Therefore, the list reported here after, reports the criteria in descending order of importance.

1. AD^2 (i.e. Advancement Degree of Difficulty) in Descending Order: remembering that AD^2 expresses the risk encountered in technology development [23], the list of technologies shall be ranked starting from those associated to higher risk in order to define, in a conservative way, the most critical technology development path;
2. Starting TRL in Ascending Order: the list of technologies shall be ranked starting from those at lower TRL in order to level out the TRL of all technologies and enable the introduction of proper flight demonstrators;
3. CaC in Ascending Order: the list of technologies shall be ranked starting from those with lower CaC in order to increase TRL of as much technologies as possible with the available budget.

The important role of AD^2 as most impacting criterion is justified considering the idea of high-risk high-gain research activities, which might be planned and funded in the upcoming years. In addition, this approach can be considered very conservative considering that it will suggest the implementation of the riskiest technology development scenario.

3.2 Elements' Definition

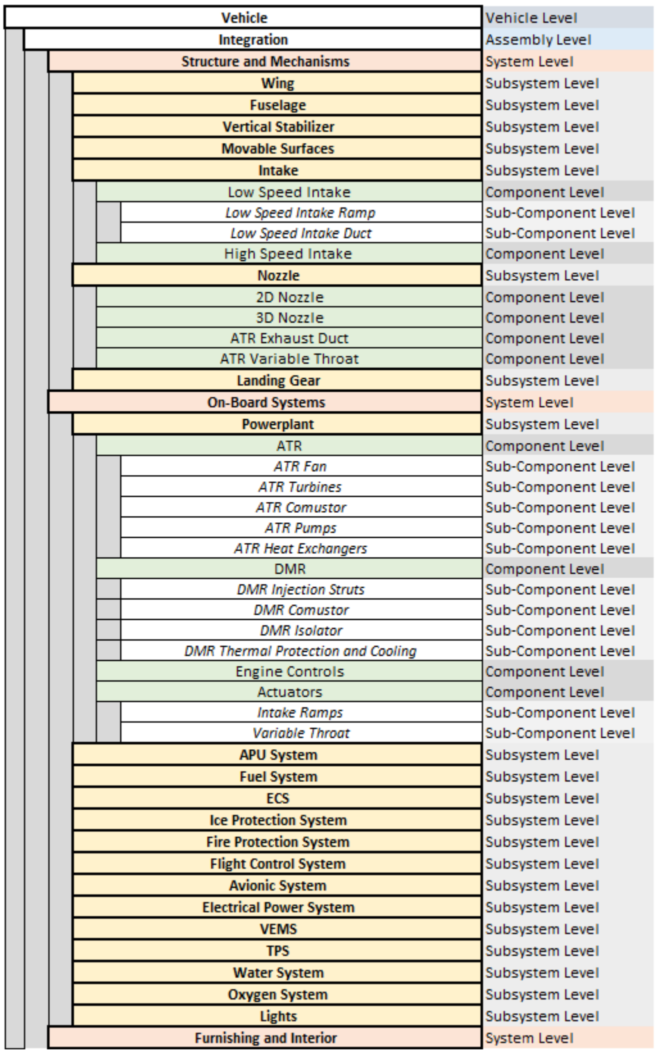
Moving forward to Step 2 (Figure 2), the list of elements to be considered in the roadmapping process shall be defined. In this analysis, considering the lack of readily available lists of elements and, as a consequence, the need to manually derive required lists, it has been decided to limit the analysis to two pillars for the specific selected TD (i.e., Propulsion): technologies and MCs. Future analyses will also encompass BBs and OCs to propose a more complete technology roadmap involving all the elements envisaged by TRIS methodology.

3.2.1 Technologies

As far as technologies' list is concerned, it has been derived starting from the vehicle Product Breakdown Structure (PBS) shown in Table 1, introducing greater detail (i.e., up to Sub-Component Level) for technologies related to Propulsion. It is worth to note that technologies in Propulsion TD, according to the PBS breakdown proposed in Table 1, belong to both Structures and Mechanisms (in particular, Intake and Nozzle) and to On-Board Systems (in particular, Powerplant). Remaining PBS elements and related technologies will not be addressed in the present analysis. As a result, starting from the PBS elements related to Propulsion TD highlighted before, the list of technologies provided in Table 2 has been derived considering elements at Component and Sub-Component Level. In Table 2, Plasma Assisted Combustion (PAC) Technology has been included as additional DMR-related technology in the framework of STRATOFLY project. The PAC is expected to induce combustion chemistry modification to ascertain continuous lean combustion, thus reducing emissions and improving fuel flexibility. Moreover, technologies with ID greater than 20 and related to Engine Materials (engines' constitutive materials, not thermal protection as expressed by technology with ID 15), Seals, Sensors and Valves have not been directly extracted from the PBS in Table 1, but they have been subsequently included in the analysis considering the detailed information related to hypersonic technology provided in [24].

At this point, to proceed towards technology roadmap derivation, all required technology data to be used in the subsequent steps of TRIS methodology (Figure 2) shall be collected or derived. These data are mainly those required to perform technology prioritization analysis and, in in this case, they are Starting TRL, CaC and AD2 for all the technologies of interest.

Table 1 Reference PBS used to derive technologies' list



Vehicle	Vehicle Level
Integration	Assembly Level
Structure and Mechanisms	System Level
Wing	Subsystem Level
Fuselage	Subsystem Level
Vertical Stabilizer	Subsystem Level
Movable Surfaces	Subsystem Level
Intake	Subsystem Level
Low Speed Intake	Component Level
Low Speed Intake Ramp	Sub-Component Level
Low Speed Intake Duct	Sub-Component Level
High Speed Intake	Component Level
Nozzle	Subsystem Level
2D Nozzle	Component Level
3D Nozzle	Component Level
ATR Exhaust Duct	Component Level
ATR Variable Throat	Component Level
Landing Gear	Subsystem Level
On-Board Systems	System Level
Powerplant	Subsystem Level
ATR	Component Level
ATR Fan	Sub-Component Level
ATR Turbines	Sub-Component Level
ATR Comustor	Sub-Component Level
ATR Pumps	Sub-Component Level
ATR Heat Exchangers	Sub-Component Level
DMR	Component Level
DMR Injection Struts	Sub-Component Level
DMR Comustor	Sub-Component Level
DMR Isolator	Sub-Component Level
DMR Thermal Protection and Cooling	Sub-Component Level
Engine Controls	Component Level
Actuators	Component Level
Intake Ramps	Sub-Component Level
Variable Throat	Sub-Component Level
APU System	Subsystem Level
Fuel System	Subsystem Level
ECS	Subsystem Level
Ice Protection System	Subsystem Level
Fire Protection System	Subsystem Level
Flight Control System	Subsystem Level
Avionic System	Subsystem Level
Electrical Power System	Subsystem Level
VEMS	Subsystem Level
TPS	Subsystem Level
Water System	Subsystem Level
Oxygen System	Subsystem Level
Lights	Subsystem Level
Furnishing and Interior	System Level

As far as Starting TRL is concerned, it is the TRL already reached by each technology at the envisaged Roadmap starting time. Starting from this value, the main goal of the roadmapping process is to foresee the activities required to increase the maturity of each technology up to reaching the, so called, Target TRL. In the present analysis, Starting TRL has been assumed as the TRL at the beginning of the H2020 STRATOFLY project in 2018, while the very final Target TRL has been supposed to be 9 for all technologies in 2050. This date (i.e. 2050) derives from the outcomes of previous roadmapping analyses for hypersonic transportation systems performed in the framework of HIKARI project [10]. In [10], a preliminary technology development schedule is proposed involving the major TDs but specific technologies are not analyzed. In addition, it is assumed that flight demonstration of the integrated system will occur around 2045. Taking this preliminary result into account, the year 2050 has been assumed as ending date for technology development in the present paper. It is probably too optimistic but it could be used to derive an initial “optimistic” scenario towards final technology maturity. This approach allows the authors to verify the achievement of one of the main H2020 STRATOFLY objectives which is the intermediate target TRL 6 to be reached by 2035. Therefore, once the complete roadmapping exercise (up to TRL 9) is available, it is necessary verify whether all the main technologies are able to reach the intermediate TRL 6 milestone by 2035.

Table 2 reports the results of the Starting TRL Assessment, manly based on the expertise of the Partners and members of the Expert External Advisory Board of the H2020 STRATOFLY project. Experts’ opinions have been then verified through an extensive literature review, also looking at the maturity of the technologies in the USA. In particular, [24] has been used as main source to compare and check the TRL of main high-speed propulsive technologies. It is worth mentioning that the TRL assessment provided in Table 2 reflects the current status of selected technologies in the European context and the comparison with available data from [24] takes into account the fact that the literature data refers to the US framework. In addition, basing on the opinions of propulsion experts involved, a preliminary assessment of AD^2 levels associated to the list *of technologies considered has been performed. Assigned values are listed in Table 2. For sake of clarity,*

Table 3 summarizes the definitions of AD² levels according to [23].

Table 2 List of technologies related to Propulsion TD and related technology data

Technology ID	**Technology Name**	**Starting TRL (@2018)**	**AD²**
1	Low Speed Intake Ramp Technology	6	3
2	Low Speed Intake Duct Technology	6	3
3	High Speed Intake Technology	4	5
4	2D Nozzle Technology	6	3
5	3D Nozzle Technology	4	6
6	ATR Exhaust Duct Technology	6	5
7	ATR Variable Throat Technology	6	5
8	ATR Fan Technology	4	8
9	ATR Turbines Technology	6	2
10	ATR Combustor Technology	6	6
11	Engine Controls Technology	7	6
12	DMR Injection Struts Technology	6	6
13	DMR Combustor Technology	4	7
14	PAC Technology	2	8
15	DMR Isolator Technology	3	8
16	DMR Thermal Protection & Cooling Technology	2	8
17	ATR Pumps Technology	6	6
18	ATR Heat Exchangers Technology	5	6
19	Intake Ramps Actuators Technology	7	5
20	Variable Throat Actuators Technology	7	5
21	Engine Cooled Materials (CMC)	4	8
22	Engine Cooled Materials (Metals)	7	7
23	Engine Uncooled Materials	4	2
24	ATR Engine Seals	3	2
25	ATR Engine Sensors	6	2
26	ATR Engine Valves	5	2
27	DMR Engine Seals	3	3
28	DMR Engine Sensors	3	3
29	DMR Engine Valves	4	3

Table 3 Definition of AD² Levels [23]

AD² Level	**Definition**
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.
8	Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be pursued.
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.
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 performance can be achieved in subsequent block upgrades with high degree of confidence.

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.
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.
3	Requires new development well within the experience base. A single development approach is adequate.
2	Exists but requires major modifications. A single development approach is adequate.
1	Exists with no or only minor modifications being required. A single development approach is adequate.

As anticipated, another important parameter in TRIS roadmapping process is CaC for each technology. Like Starting TRL and AD^2, CaC has been defined as one of the prioritization criteria. Considering the lack of real cost data for hypersonic transportation systems and more specifically for hypersonic technologies, CaC has been assessed by the authors from Politecnico di Torino thanks to their expertise in parametric cost estimation methodologies for high-speed vehicles. In particular, lacking a detailed cost estimation for STRATOFLY MR3 vehicle, the result of cost estimation related to LAPCAT MR2.4 (precursor of STRATOFLY MR3) previously performed by Politecnico di Torino and reported in [25] has been here exploited as main source of cost data. In particular, Research, Development, Test and Evaluation (RDTE) cost, Theoretical First Unit (TFU) Production cost and Total Operating Cost (TOC) per flight available from [25] are collected in Table 4.

Table 4 Reference Life Cycle Costs for LAPCAT MR2.4

Cost Item	**Cost [M€ FY 2017]**
Vehicle RDTE	24982
Vehicle TFU Production	1401
Initial Operations (5 Flights)	4.77
Vehicle CaC (up to TRL 9)	26387.77
RDTE 1	23408.60
RDTE 2	1573.40
RDTE 1/ Vehicle RDTE	94%
Powerplant RDTE (ATR + DMR)	7343
Powerplant RDTE 1	6880.53

Starting from these data, a relationship between costs (i.e. RDTE, TFU Production and TOC) and TRL transits has been derived starting from the relation between (high) TRL milestones and Project Phases suggested by ESA in [26] and depicted in Figure 5 (right). The proposed relationship in Figure 5 (left) is specifically tailored for future reusable hypersonic transportation systems and it assumes that the production phase envisaged between TRL 6 and TRL 8 is strictly related to the production of flight demonstrators (i.e., prototype vehicles). Between TRL 8 and 9 starts series-production with the TFU production and, at the same time, the operation phase begins using the actual flight vehicle. RDTE costs are assumed to cover all the TRL milestones up to TRL 9, when development phase officially ends. In account of this, considering the subdivision proposed in Figure 5 (left), it is possible to derive the CaC as the sum of total RDTE cost, TFU Production an Initial Operations. For sake of clarity, the first portion of CaC up TRL 8 including only a fraction of RDTE cost is labelled “RDTE 1” in Figure 5 (left), while the portion of CaC between TRL 8 and 9 is constituted by the remaining part of RDTE (labelled as “RDTE 2”), TFU Production and Initial Operations Costs. In particular, it has been assumed that initial Operations include 5 flights in line with the Space Shuttle, for which the DDTE phase officially ended with the 5th Columbia orbital flight according to [20]. Thanks to the relationship between Vehicle CaC and Life Cycle Cost (LCC) just discussed, it is now possible to allocate available cost data for LAPCAT MR2.4 onto TRL Transits. In particular, remembering the general validity of Eq. (1), from Eq. (2) it is possible to derive RDTE 1 and from Eq. (3) RDTE 2 exploiting the newly derived CaC distribution depicted in Figure 4**Error! Reference source not found.**. All numerical values for the v ariables here introduced are reported in Table 4.

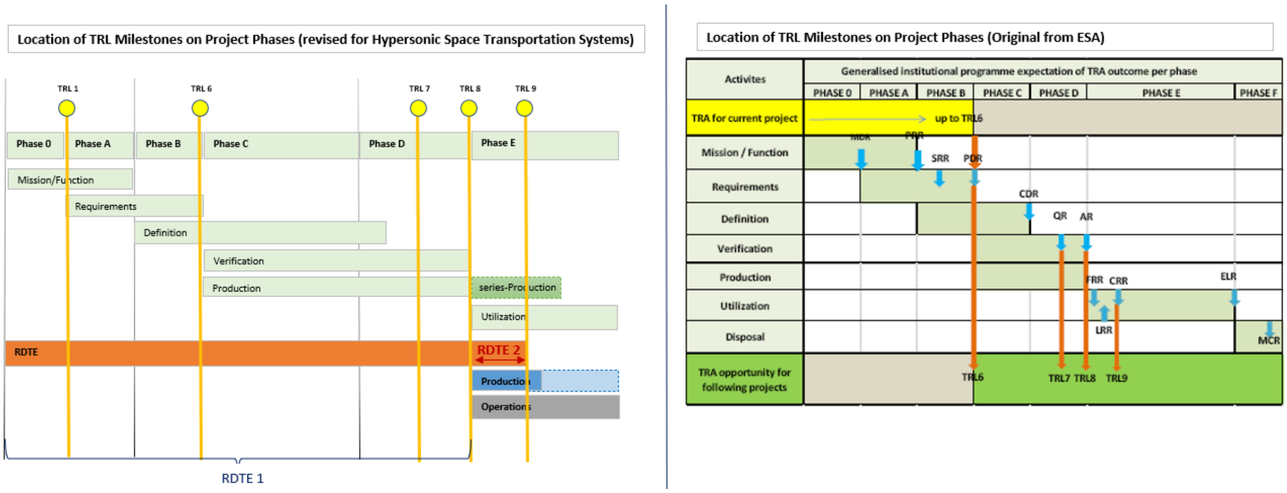


Figure 5 Location of TRL Milestones on Project Phases: original ESA subdivision [26] *(right) vs. revised version for hypersonic*

$$RDTE = RDTE\ 1 + RDTE\ 2 \tag{1}$$

$$RDTE\ 1 = 88.71\%\ Vehicle\ CaC\ (up\ to\ TRL\ 9) \tag{2}$$

$$RDTE\ 2 + Vehicle\ TFU\ Production + Initial\ Operations = 11.29\%\ Vehicle\ CaC\ (up\ to\ TRL\ 9) \tag{3}$$

At this point, the basic idea is to allocate Vehicle CaC onto technologies and then apply the CaC distribution at technology level to derive the cost contribution of each TRL transit. Before proceeding, it is worth specifying that the allocation of Vehicle CaC onto technologies is effectively applicable up to TRL 8: indeed, it appears meaningless to split TFU Production Cost and Initial Operations cost onto technologies because from TRL 8 all technologies are physically integrated into the actual flight vehicle. In account of this, it has been decided to allocate onto technologies only the costs sustained up to TRL 8, i.e., RDTE 1 component.

Furthermore, considering the lack of any cost information at technology level, it was judged not feasible to directly allocate RDTE 1 onto technologies listed in Table 2. Therefore, as intermediate step, it has been decided to firstly consider the costs subdivision on PBS elements and then proceed with allocation onto technologies. More specifically, recalling the RDTE cost subdivision onto PBS elements for LAPCAT MR2.4 reported in Figure 6 [25], it can be inferred that the PBS elements considered in the current analysis are ATR, DMR and STRUCT (i.e. Structure and Mechanisms). It is specified that DMR and ATR PBS components shown in Figure 6 represent overall Powerplant contribution to RDTE cost. Therefore, it can be stated that Engine Controls and Actuators (included in Powerplant in Table 1) are included into them. In addition, it is highlighted that the STRUCT component depicted in Figure 6 includes all the vehicle structural elements, in particular, wing, body, intake, nozzle and landing gear. Remembering that, for the purposes of the present analysis, only the contribution of propulsion plant-related structural components is considered, the RDTE component allocated to STRUCT has been further subdivided to assess the impact of intake and nozzle onto costs and then derive the costs of associated technologies. This has been performed exploiting additional results related to LAPCAT MR2.4 obtained at Politecnico di Torino and depicted in Figure 7. The latter shows the impact of specific components such as nozzle and intake onto STRUCT RDTE costs (which in turn is 43% of total RDTE cost as shown in Figure 6). From these data, it has been possible to assess the impact on Vehicle RDTE cost of specific technologies belonging to Structure and Mechanisms as summarized in Table 5. Vehicle RDTE fraction related to Nozzle and Intake (last column of Table 5) has been then equally split between related technologies (3 technologies for intake and 4 for nozzle). Results of this analysis are summarized in Table 6, where obtained fractions of Vehicle RDTE cost at technology level have been applied to RDTE 1 to obtain technologies' CaC up to TRL 8 (last column of Table 6). The latter can be easily split in to TRL Transits (TRL 0 to TRL 1, TRL 1 to TRL 2, etc. up to TRL 7 to TRL 8) exploiting the breakdown in Figure 4**Error! Reference source not found.**.

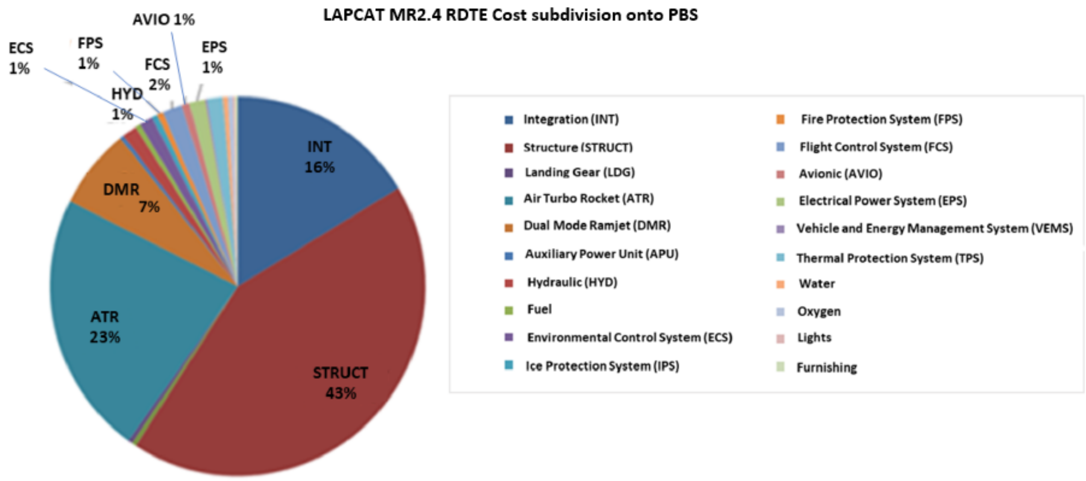


Figure 6 LAPCAT MR2.4 RDTE cost subdivision onto PBS [25]

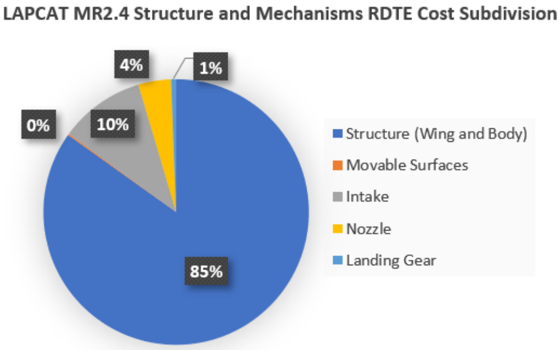


Figure 7 LAPCAT MR2.4 Structure and Mechanisms RDTE cost subdivision

Table 5 Subdivision of STRUCT RDTE cost onto components for LAPCAT MR2.4

STRUCT Components	**STRUCT RDTE Breakdown [%]**	**STRUCT RDTE as % of Vehicle RDTE**	**STRUCT Components RDTE as % of Vehicle RDTE**
Structure (Wing and Body)	84.85%	43%	36.49%
Movable Surfaces	0.16%		0.07%
Intake	10.40%		4.47%
Nozzle	3.98%		1.71%
Landing Gear	0.60%		0.26%
Total	**100.00%**		**43.00%**

Table 6 RDTE cost for Structure & Mechanisms technologies

Structure & Mechanisms Technologies	**RDTE as % of Vehicle RDTE**	**CaC (up to TRL 8) [M€ 2017]**
Low Speed Intake Ramp Technology	1.49%	349.04
Low Speed Intake Duct Technology	1.49%	349.04
High Speed Intake Technology	1.49%	349.04
2D Nozzle Technology	0.43%	100.16
3D Nozzle Technology	0.43%	100.16
ATR Exhaust Duct Technology	0.43%	100.16
ATR Variable Throat Technology	0.43%	100.16

As far as Powerplant technologies are concerned, available RDTE cost breakdown on PBS provided in Figure 6 splits costs between ATR and DMR without providing information for the elements related to both propulsive components. This is the case of Engine Controls, Actuators, and Engine Materials and related technologies (see Table 1 and Table 2 for more details), which are referred both to ATR and DMR and, more in general, they might be assigned to Powerplant. In this case, detailed cost information as for Structure and Mechanisms components (Figure 7) was not available so that a different strategy has been adopted to derive technologies' costs for Engine Controls, Actuators, and Engine Materials. In particular, basing on the comments collected from propulsion experts, a preliminary estimation of RDTE effort to develop propulsive technologies has been performed by assigning a level (high, moderate, moderate-high, low-moderate, low) to each technology. Each level has been then associated to a number (or "weight") in order to derive the cost contribution of each propulsion technology basing on the estimated level of effort assigned. Results of this analysis are reported in Table 7 where, for each technology related to Powerplant, it is reported the estimated RDTE Effort Level, the associated numerical weight and the derived percent impact onto total Powerplant RDTE Cost. The latter is given by the sum of ATR and DMR RDTE cost from [25] and it is reported in Table 4. In order to obtain technologies' CaC up to TRL 8 in analogy to what performed for Structure and Mechanisms technologies, obtained percentages (see 5th column of Table 7) have been applied to Powerplant RDTE 1 reported in Table 4, which represent the estimated RDTE required to reach TRL 8 for the Powerplant. It has been derived as a fraction of Powerplant RDTE (up to TRL 9) considering Powerplant RDTE 1/ Powerplant RDTE equal to RDTE 1/ Vehicle RDTE (Table 4). After applying the percentages at the 5th column of Table 7 (representing the share of each propulsive technology on Powerplant RDTE) to Powerplant RDTE 1, the estimated CaC up to TRL 8 has been obtained for each technology as provided in Table 7.

Table 7 RDTE cost for propulsive technologies

Reference PBS Element	Powerplant Technology	Estimated RDTE Effort Level	Level "Weight"	Powerplant RDTE Cost [%]	CaC (up to TRL 8) [M€ 2017]
ATR	ATR Fan Technology	MODERATE-HIGH	2	10%	679.56
	ATR Turbines Technology	LOW	0.3	1%	101.93
	ATR Combustor Technology	LOW-MODERATE	1.5	7%	509.67
	ATR Pumps Technology	LOW-MODERATE	1.5	7%	509.67
	ATR Heat Exchangers Technology	LOW-MODERATE	1.5	7%	509.67
	ATR Engine Seals	LOW	0.25	1%	84.94
	ATR Engine Sensors	LOW	0.25	1%	84.94
	ATR Engine Valves	LOW	0.25	1%	84.94
DMR	DMR Injection Struts Technology	LOW	0.3	1%	101.93
	DMR Combustor Technology	LOW-MODERATE	1.1	5%	373.76
	PAC Technology	LOW	0.3	1%	101.93
	DMR Isolator Technology	LOW-MODERATE	1.1	5%	373.76
	DMR Thermal Protection & Cooling Technology	LOW-MODERATE	1.1	5%	373.76
	DMR Engine Seals	LOW	0.3	1%	101.93
	DMR Engine Sensors	LOW	0.3	1%	101.93
	DMR Engine Valves	LOW	0.3	1%	101.93
Engine Controls	Engine Controls Technology	LOW	1	5%	339.78
Actuators	Intake Ramps Actuators Technology	LOW	1	5%	339.78
	Variable Throat	LOW	1	5%	339.78

	Actuators Technology				
(Engine Materials)	Engine Cooled Materials (CMC)	HIGH	3	15%	1019.34
	Engine Cooled Materials (Metals)	LOW-MODERATE	1.5	7%	509.67
	Engine Uncooled Materials	LOW	0.4	2%	135.91

3.2.2 Mission Concepts

Once all information related to technologies is collected, it is possible to move towards the definition of MCs, which represent all the activities required to increase TRL for a specific technology. In order to derive a complete list of MCs spanning all TRL levels for each technology, the definition of TRL levels provided in [26] have been thoroughly considered. In addition, with the aim to suggest a set of MCs specifically tailored for propulsion technologies development (particularly at low TRL levels) several literature sources describing the development of advanced propulsive subsystems, such as ATREX and S-Engine in Japan [27]–[29], have been considered. Moreover, information useful to propose flight demonstration missions at higher TRLs has been extracted from [24], where an analysis of flight demonstrations for future access to space vehicles is proposed. In particular, basing on the information in [24], it has been possible to suggest the following flight demonstration missions for the STRATOFLY vehicle:

- Flight Demo 1a: 6-10 Small Scale Vehicle(s) (1/10 of full-scale cruiser), recoverable (not reusable) allowing to characterize hypersonic environment at different flight conditions in the Mach range 3 to 8;
- Flight Demo 1b: 3 Mid Scale reusable vehicles (1/3 scale engine) able to perform 6-9 flight tests in the Mach range 3 to 8;
- Flight Demo 2: 2 Near Full Scale reusable vehicles allowing to test the whole spectrum hypersonic conditions encountered during the final mission (Mach 0 to 8).

Considering that all technologies under analysis belong to the same TD (i.e., Propulsion), it has been assumed that these Flight Demos are applicable to all technologies in Table 2. Moreover, remembering the TRL definitions provided in [26], it has been assumed that, once both completed, Flight Demo 1a and 1b would enable the TRL transit from 6 to 7, while Flight Demo 2 the TRL transit from TRL 7 to 8. As a result, a complete list of MCs required to progress up to TRL 9 has been derived for each technology, including both the technology-specific MCs required at low TRLs and the more complex an integrated MCs (i.e., Flight Demonstrators) performed at higher TRLs. An example of the list of MCs related to Low Speed Intake Ramp Technology is shown in Table 8, providing for each MCs both the start TRL and the TRL reached at the end of the mission. It is worth specifying that, in case several MCs are connected to the same Start TRL, it means that they shall be all successfully performed in order to effectively succeed in the TRL transit. Similar lists have been derived for all the other technologies in Table 2, taking into account that some MCs at higher TRLs could be shared by several technologies. Depending on the estimated Starting TRL for each technology, it is possible to assess which MCs are still to be performed in order to reach Target TRL and which have already been done in the past. Therefore, this analysis allows not only to predict the MCs required for future technology development but also to re-build the complete history since the beginning of RDTE activities at technology level.

Table 8 List of MCs for Low Speed Intake Ramp Technology

MC Name	**Start TRL**	**End TRL**
Expression of basic principles for intended use of Low Speed Intake Ramp Technology	0	1
Identification of potential applications of Low Speed Intake Ramp Technology	0	
Design of Low Speed Intake Ramp, providing understanding of how the basic principles are used.	1	2
Formulation of potential application of Low Speed Intake Ramp Technology	1	

General definition of performance requirements for Low Speed Intake Ramp Technology	1	
Low Speed Intake Design	2	3
Low Speed Intake Numerical Analysis/Simulation	2	
Design of low speed intake model for wind tunnel test (not yet integrated into engine model)	3	4
Fabrication of low speed intake model(s) for wind tunnel test(s)	3	
Wind tunnel test(s) of low speed intake model(s)	3	
Design of low speed intake model to be integrated into propulsion plant wind tunnel model	4	5
Fabrication of low speed intake model(s) to be integrated into propulsion plant wind tunnel model(s)	4	
Propulsion Plant Wind tunnel test(s) to verify critical functions	4	
Design of low speed intake model to be integrated into propulsion plant model	5	6
Fabrication of low speed intake model(s) to be integrated into propulsion plant model(s)	5	
Sea-level firing test(s) of propulsion plant model(s)	5	
Design of low speed intake model to be integrated into Small Scale Flight Demonstrator	6	7
Fabrication of low speed intake model(s) to be integrated into Small Scale Flight Demonstrator(s)	6	
Flight test(s) of Small Scale Flight Demonstrator(s)	6	
Design of low speed intake model to be integrated into Mid Scale Flight Demonstrator	6	
Fabrication of low speed intake model(s) to be integrated into Mid Scale Flight Demonstrator(s)	6	
Flight test(s) of Mid Scale Flight Demonstrator(s)	6	
Design of low speed intake model to be integrated into Near Full Scale Flight Demonstrator	7	8
Fabrication of low speed intake model(s) to be integrated into Near Full Scale Flight Demonstrator(s)	7	
Flight test(s) of Near Full Scale Flight Demonstrator(s)	7	
STRATOFLY MR3 Mission(s)	8	9

3.3 Prioritization

Once the lists of elements (i.e., Technologies and MCs in this specific application) are derived, it is possible to move to prioritization studies. The latter, through a proper trade-off analysis, allows to rank the list of technologies according to the criteria defined by Stakeholders exploiting the technology data gathered in Table 2. In particular, available technology data in Table 2 have been firstly normalized according to the order (ascending/descending) assigned by EC stakeholder to related criteria as shown in Table 9 and

Table 10. Moreover, basing on the ranking assigned to each criterion, a specific weight has been associated to each criterion. In the present example, considering the criteria ranking introduced above, the following weights have been considered:

- AD2: 50%;

Starting TRL: 33% (labeled as TRL in Table 9 and

- Table 10);
- CaC: 17%

These criteria weights have eventually been applied to the normalized technology data (matrix product) in order to obtain the ranked list of technologies shown in Figure 8.

Table 9 Normalization of technology data (Part 1)

	Technology ID													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
AD^2	0.24	0.24	0.24	0.85	0.85	0.85	0.85	0.12	0.83	0.17	0.25	0.83	0.23	0.83
TRL	0.33	0.33	0.50	0.33	0.50	0.33	0.33	0.50	0.33	0.33	0.29	0.33	0.50	1.00

CaC	0.38	0.38	0.63	0.38	0.75	0.63	0.63	1.00	0.25	0.75	0.75	0.75	0.88	1.00
Tot.	0.34	0.34	0.52	0.44	0.68	0.56	0.56	0.69	0.37	0.51	0.51	0.62	0.64	0.97

Table 10 Normalization of technology data (Part 2)

	Technology ID														
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
AD^2	0.23	0.23	0.17	0.17	0.25	0.25	0.08	0.17	0.62	1.00	1.00	1.00	0.83	0.83	0.83
TRL	0.67	1.00	0.33	0.40	0.29	0.29	0.50	0.29	0.50	0.67	0.33	0.40	0.67	0.67	0.50
CaC	1.00	1.00	0.75	0.75	0.63	0.63	1.00	0.88	0.25	0.25	0.25	0.25	0.38	0.38	0.38
Tot.	0.76	0.87	0.51	0.54	0.45	0.45	0.68	0.56	0.40	0.51	0.40	0.43	0.55	0.55	0.49

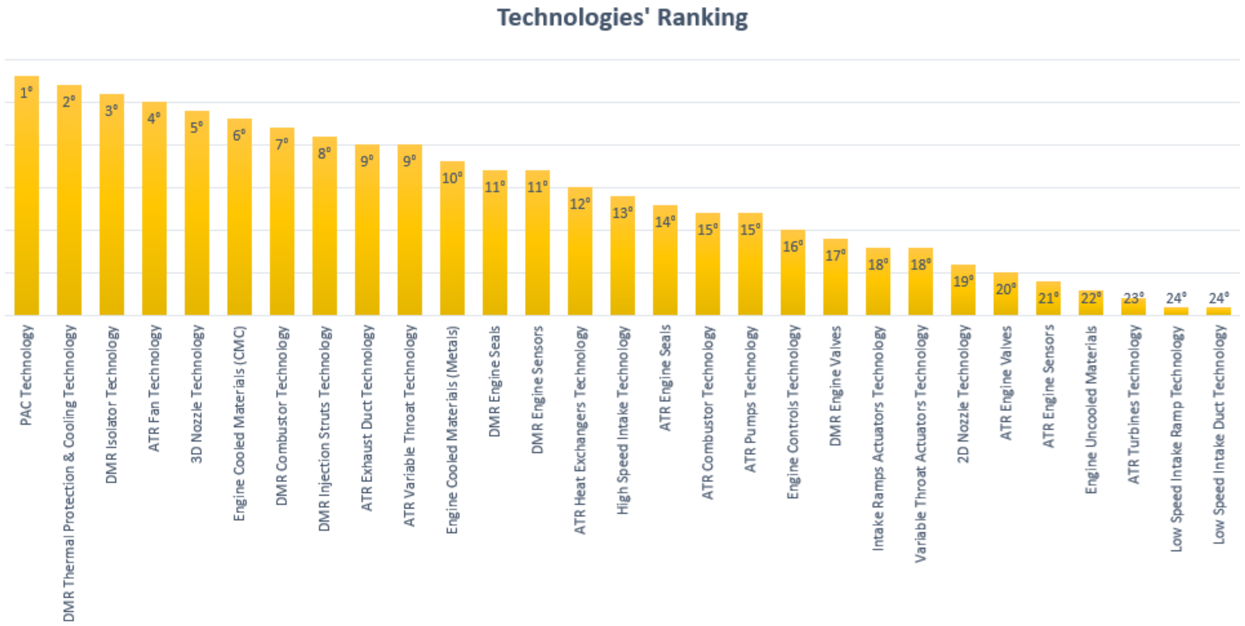


Figure 8 Final technologies' ranking

3.4 Planning

As introduced, the final step of TRIS methodology (Figure 2) proposes a Planning for technology development taking into account the results of prioritization analyses. In particular, it allows to order in a logical way the list of MCs linked to technologies not only considering the preferences expressed by stakeholders but also the effective possibility to perform each MC depending on the technology maturation attained. In detail, as depicted in the flowchart of Figure 9, the Planning routine considers the ranked list of n technologies (referred as "List A" in Figure 9). Then, starting from the first technology (i.e., $\text{Tech}_{i=1}$) in List A, its Starting TRL (or current TRL, i.e., TRL_{curr_i}) is compared to Target TRL (i.e., $\mathrm{TRL}_{\mathrm{Target}}$, which is the same for all technologies in the list). Only in case technology development is effectively required (i.e., $TRL_{curr_i} < \mathrm{TRL}_{\mathrm{Target}}$), the list of N MCs (referred as "List B" in Figure 9) allowing to increase TRL_{curr_i} to $TRL_{curr_i} + 1$ is considered. Indeed, as shown in Table 8, it has been assumed that several MCs might be required to increase TRL of a unitary step. At this point, 2 options are possible:

- MC_j in List B is linked only to $\text{Tech}_{i=1}$: MC_j can be selected for the final MCs Planning and it is possible to consider the next MC in List B in order to include all MCs required to fulfill the specified TRL transit, or
- MCj in List B is linked to $\text{Tech}_{i=1}$ and to other technologies at lower priority: MC_j can be included in the final MCs Planning only if all linked technologies already reached MC_j enabling TRL. In this case, the next MC in List B may be considered. Otherwise, MC_j cannot be envisaged yet because the maturity level of all linked technologies is not sufficient to enable that MC. Therefore, the loop into List B is exited (i.e., the specified TRL transit cannot be fulfilled at the

moment) and the analysis moves to the subsequent technology in the ranking in order to enable all pending MCs.

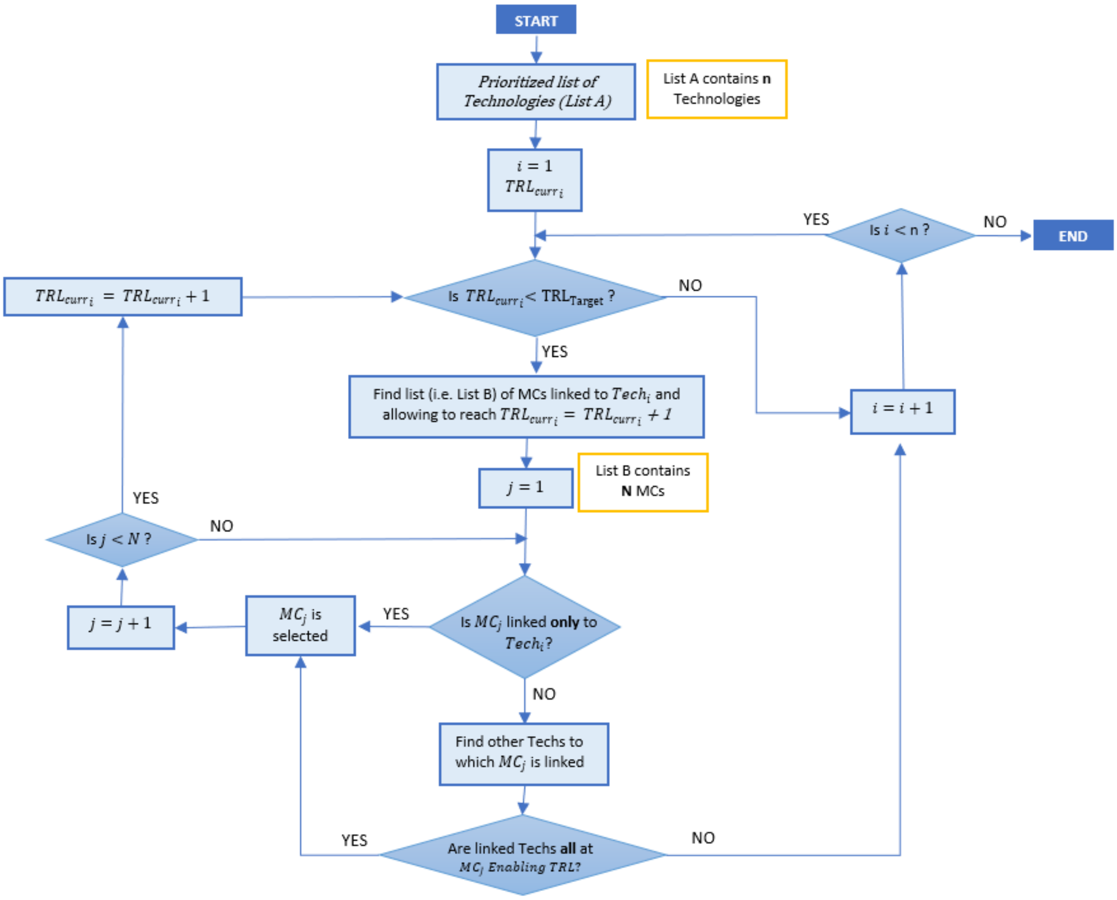


Figure 9 MCs planning flowchart

Once all technologies are considered, an ordered list of MCs to pursue technology development is suggested, taking into account the effective possibility to integrate different technologies into a unique demonstrator only once required maturity for all. It is specified that the ordered list of MCs here derived could represent a fundamental tool in the phase of budget allocation. In particular, supposing that only limited resources are available for technology development, it suggests the MCs that should have higher priority in order to accomplish stakeholders' expectations.

To complete the analysis, the ordered list of MCs shall be properly distributed on a timeline in order to verify that the initial goal (i.e., TRL 6 by 2035) has been achieved. To do so, the envisaged duration of TRL transits for hypersonic transportation systems has been assessed using the time distribution reported in Figure 4 (right). In particular, the time breakdown in **Error! Reference source not found.** has been exploited to derive a preliminary development timeline for each technology. For example, considering that "Low Speed Intake Ramp Technology" was at TRL 6 in 2018 and, as projected, it will be at TRL 9 in 2050, according to **Error! Reference source not found.**, 44% of total development time (or time at completion) is accomplished in 11688 days (for sake of clarity, between 01/01/2018 and 01/01/2050). From this information, time at completion may be easily assessed and, as a result, the days required to perform each TRL transit may be estimated by applying again the breakdown in **Error! Reference source not found.**. In this way, basing on the estimated duration of each TRL transit, it has been possible to determine, for each technology, the date in which each TRL milestone could be achieved. The preliminary timeline derived for each technology has been then refined taking into account the MCs to be performed during each TRL transit. In particular, considering MCs linked to several technologies, they could start only once all related technologies have reached the MC enabling TRL. For example, assume that a generic MC1 is enabled (i.e., it may be effectively performed) at TRL4 and that it is linked to Tech 1, Tech 2 and Tech 3. Thanks to the preliminary timeline derived, the estimated dates in which Tech 1, Tech 2 and Tech 3 reach TRL 4 are available (respectively Date 1, Date 2 and Date 3). Assuming that Date 1 < Date 2 < Date 3, MC1 may effectively start at Date 3, when all technologies will reach the required TRL milestone. Similar considerations have been applied to all the technologies under analysis. More specifically, merging the preliminary timelines derived for each technology with the ordered list of MCs previously discussed, it has been possible to obtain the final planning shown in Figure 10 and Figure 11. The so-called “Technology Gap” shown in Figure 10 and Figure 11 highlights, for some of the technologies under consideration, the need to freeze the technology development at a specific TRL in order to enable, with the development of the remaining technologies, the MCs required to proceed towards the next milestone. From the timelines depicted in Figure 10 and Figure 11 it may be observed that all technologies may reach TRL 6 by 2035 if no out-of-nominal events occur and, most importantly, if available budget will be sufficient to cover the CaC of all technologies.

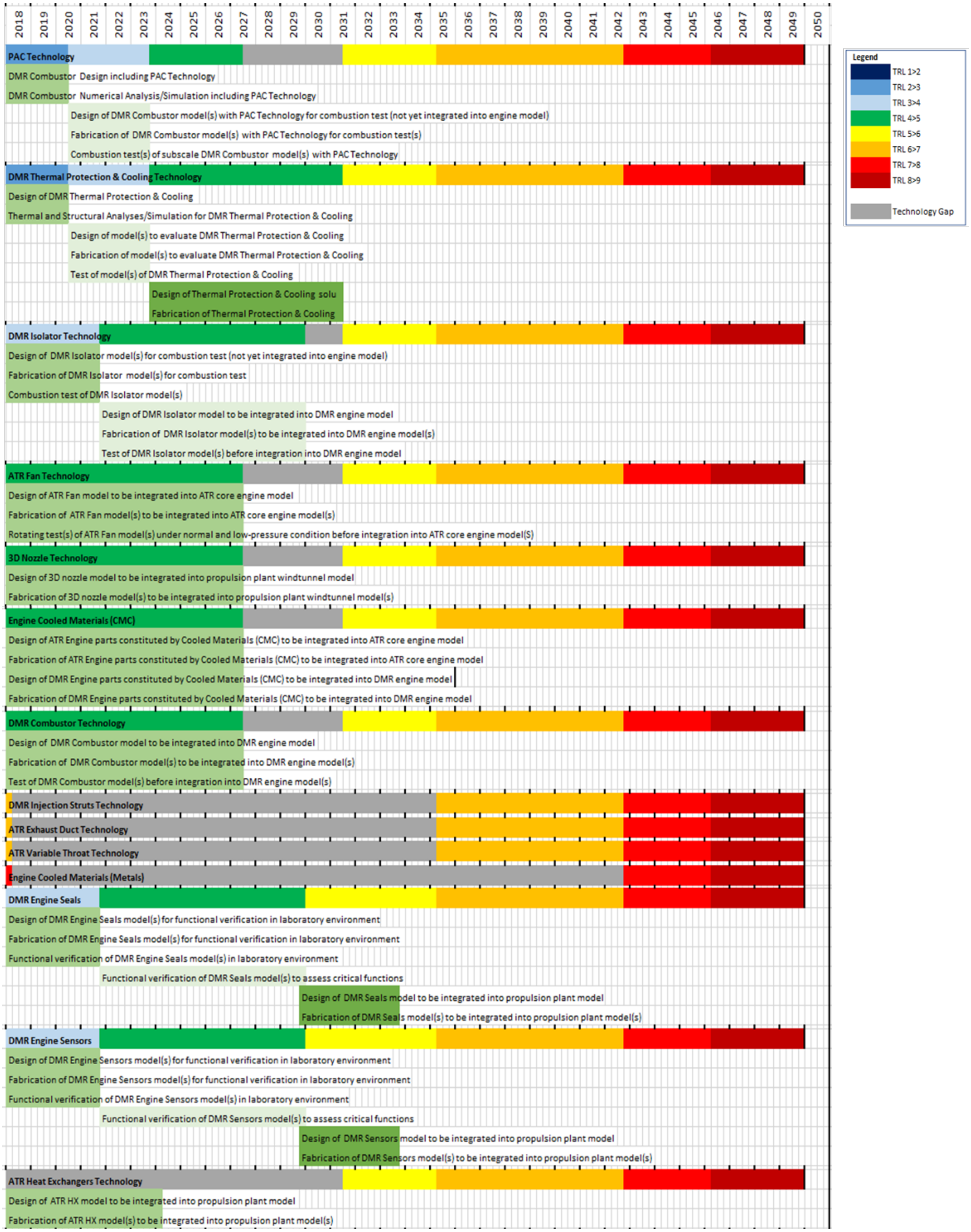


Figure 10 Final Technologies' and MCs Planning up to 2050 (Part 1)

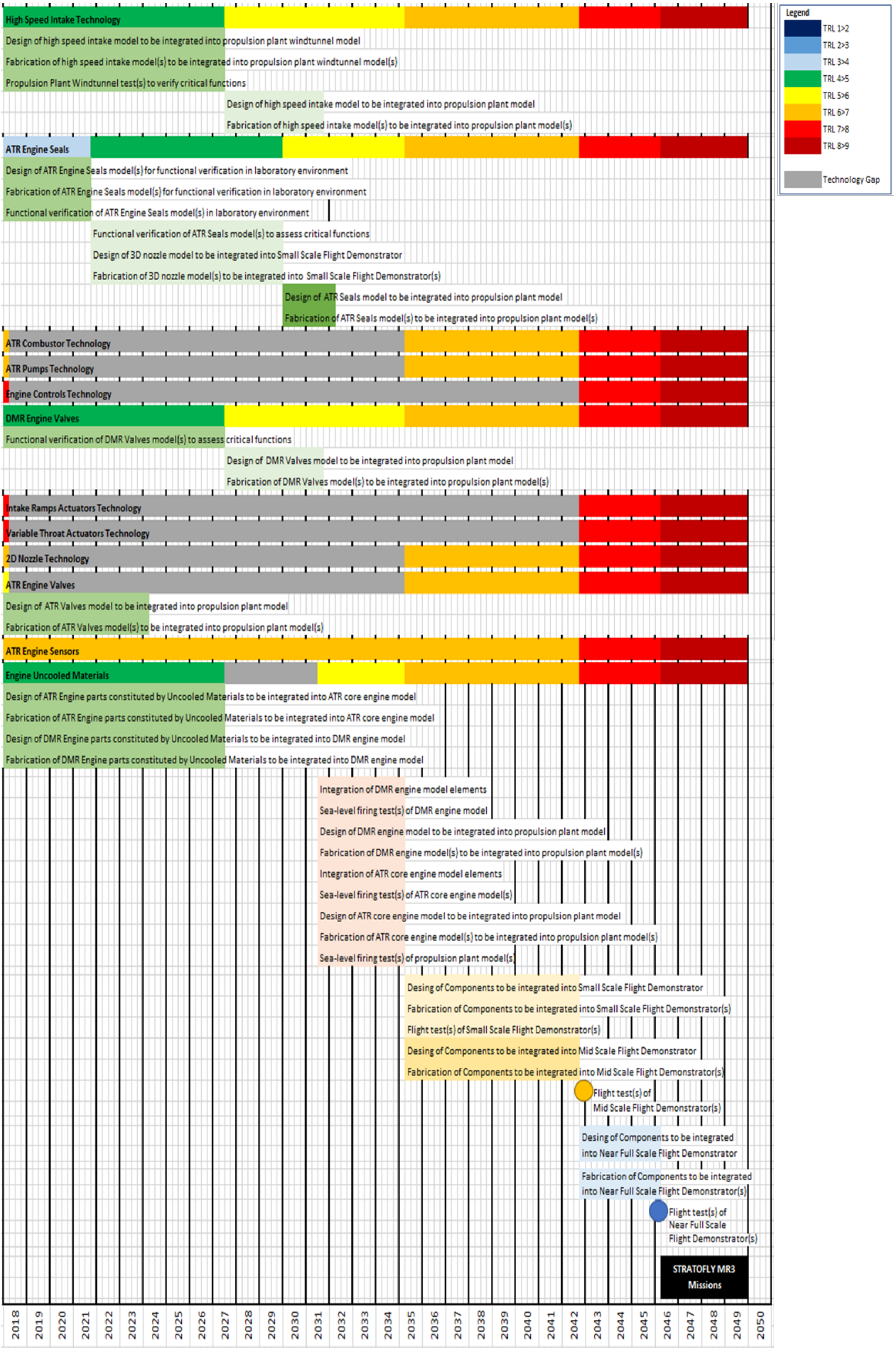


Figure 11 Final Technologies' and MCs Planning up to 2050 (Part 2

4. Conclusion

In conclusion, this paper proposes a preliminary technology roadmap for a set of propulsive technologies analyzed in the framework of the H2020 STRATOFLY project. On the basis of the authors' expertise, the technology roadmapping methodology has been improved to better deal with the hypersonic case study. In details, two main innovative aspects have been disclosed: a new estimation of CaC for each TRL transit and a new estimation of time request for each TRL transit, specifically tailored for hypersonic transportation. The applicability of TRIS methodology to STRATOFLY has been verified, highlighting the capability of the technology roadmapping approach studied at Politecnico di Torino to deal with a wide range of case studies in the framework of complex aerospace systems. In addition, basing on specific assumptions, the effective possibility to reach TRL 6 by 2035 as intermediate milestone has been verified, suggesting a possible incremental path toward the final maturation of technologies foreseen by 2050. Future analyses will deal with the extension of the proposed roadmap to technologies belonging to other TDs (i.e., Thermal, Structures and Mechanisms, etc.) in order to propose a more complete overview of the technology development steps for the main disciplines analyzed in STRATOFLY. Moreover, the sensitivity of results to criteria, time and budget constraints will be studied verifying whether the TRL goal for 2035 can still be achieved.

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Copyright Statement

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