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Acta Astronautica 195 (2022) 430–444

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Technology roadmapping methodology for future hypersonic transportation systems

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ARTICLE INFO

Keywords:
Technology roadmap
Technology assessment
Hypersonic transportation

ABSTRACT

This paper discloses an innovative methodology for the generation and update of technology roadmaps to support strategic decisions for future hypersonic transportation systems, specifically targeting non-profit oriented R&D. The methodology is fully integrated into up-to-date conceptual design activity flows. It consists of five main steps that through mathematical and logical models moves from stakeholders' analysis up to planning definition and results evaluation. Complementary to the traditional experts-based methodologies, the rational process here presented allows for a well-structured logical definition of activities and/or missions required to enhance the readiness level of technologies, including a more accurate and reliable budget and time resources estimation to support the technology development plan. This methodology is exploited in the framework of the H2020 STRATOFLY Project to assess the potential of hypersonic civil vehicles to reach Technology Readiness Level 6 by 2035 with respect to key technological, societal and economical aspects. The paper discloses a unique assessment of the readiness level of the European air-breathing propulsive technologies. The final results confirm the crucial role of air-breathing propulsive technologies in the development of future hypersonic transportation system and highlight the urgent need to invest in in-flight demonstration missions with increasing functionalities, to target 2050 as entry in to service of the first Mach 8 civil transport.

1. Introduction

The mastering of technologies to enable future high-speed transportation systems is a worldwide challenge: to compete in such an innovative and dynamic context, technology roadmapping methodologies and tools are key players in establishing priorities in technology development. On the basis of well-defined performance target for the final product, technology roadmapping methodologies can support the identification of enabling technologies along with the activities required to pursue technology development, operational capabilities and building blocks involved, taking into account possible alternatives as well as stakeholders' needs and expectations [1].

Since the mid-2000s, several efforts have been spent to increase the readiness level of enabling technologies of hypersonic transportation systems without following a well-structured path. In Europe, to enhance hypersonic transportation capabilities, the European Commission (EC) with the participation of the European Space Agency (ESA) along with partners from industry, universities, and research centres, co-funded dedicated research activities, such as Long-Term Advanced Propulsion Concepts and Technologies (LAPCAT) I and II projects [2–4], Aerodynamic and Thermal Load Interactions with Lightweight Advanced Materials for High-Speed Flight (ATLLAS) I and II projects [5,6], High-Speed Experimental Fly Vehicles (HEXAFLY) and HEXAFLY-INTernational projects [7,8], and Future High-Altitude High-Speed Transport 20XX (FAST 20XX) project [9,10]. Making benefit of the heritage from these previous European research activities, in 2018 the EC funded a new Horizon 2020 (H2020) project called Stratospheric Flying Opportunities for High-Speed Propulsive Concepts (STRATOFLY) [11,12], aiming 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. For the first time, the crucial role of technology roadmapping has been recognized and specific efforts have been spent to upgrade already available technology roadmapping methodologies to widen the applicability to the specific case of hypersonic transportation. In this context, the Technology RoadmappIng Strategy (TRIS) methodology and tool developed at Politecnico di Torino [13] has been considered as reference, upgraded and exploited to give priorities in terms of technologies and activities to be planned to meet the ambitious target of the H2020 STRATOFLY project. In Ref. [13], a first upgrade of technology roadmapping methodologies for space transportation systems [14–16] to

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https://doi.org/10.1016/j.actaastro.2022.03.038
Received 26 October 2021; Received in revised form 22 March 2022; Accepted 29 March 2022
Available online 1 April 2022

Nomenclature

Latin Symbols

$\frac{DOC_C}{Flight}$ Direct Operating Cost for crew per flight [€]
$\frac{DOC_D}{Flight}$ Direct Operating Cost for depreciation per flight [€]
$\frac{DOC_{Fuel}}{Flight}$ Direct Operating Cost for fuel per flight [€]
$\frac{DOC_I}{Flight}$ Direct Operating Cost for insurance per flight [€]
$\frac{DOC_M}{Flight}$ Direct Operating Cost for maintenance per flight [€
f_0 Systems engineering integration factor for development
f_{4_j} learning curve factor associated to the jth engine of a specified type produced
f_6 delay factor
f_7 program organization factor
F_V Theoretical First Unit Production cost for high-speed advanced aircraft [WYr]
H_{Ei} Research, Development, Test & Evaluation cost of engine (of a specified type) [WYr]
H_{VA} Research, Development, Test & Evaluation cost of high-speed advanced aircraft [WYr]
$\frac{IOC}{Flight}$ Indirect Operating Cost per flight [€]
K_1 percentage of Vehicle Cost at Completion up to Technology Readiness Level 8
K_{CAD2} weight of Advancement Degree of Difficulty criterion
K_{CCaC} weight of Cost at Completion criterion
K_{Cij} weight of jth criterion asked by ith stakeholder
K_{CTRL} weight of Starting Technology Readiness Level criterion
$K_{Powerplant}$ contribution of powerplant to Vehicle Cost at Completion up to Technology Readiness Level 8
K_{SG_i} ith stakeholder weight according to his/her position on the Strategy Grid
K_{TDj} cost contribution of jth Technology Domain onto Product Breakdown Structure
$K_{TD_{Structures}*}$ contribution of nozzle and intake-related technologies to Vehicle Cost at Completion up to Technology Readiness Level 8
$K_{Tech\ i}$ weight associated to generic ith technology
$K_{Tech\ i\ Powerplant}$ weight associated to ith technology belonging to powerplant
$K_{Tech\ i\ TD_{Structures}*}$ weight associated to ith technology belonging to $TD_{Structures}*$
$K_{Tech\ i\ TD_{Structures}*(Intake)}$ weight associated to ith technology belonging to $TD_{Structures}*$ and related to intake
$K_{Tech\ i\ TD_{Structures}*(Nozzle)}$ weight associated to ith technology belonging to $TD_{Structures}*$ and related to nozzle
MC_j jth Mission Concept
n_e number of engines of a specified type installed on the vehicle
n_E number of engine types installed
$n_{init.\ ops}$ number of flights assumed for initial operations
$TD_{Structures}$ Structures Technology Domain
$TD_{Structures}*$ portion of Structures Technology Domain including nozzle and intake components
$Tech_i$ *i* th technology
$Technologies_{\ Powerplant}$ technologies belonging to powerplant
$Technologies_{\ TD\ Structure*}$ nozzle and intake-related technologies belonging to Structures Technology Domain
$Technology\ CaC_i$ CaC of ith technology
$Technology\ CaC_{ij}$ CaC of ith technology belonging to jth Technology Domain
$Technology\ CaC_{i\ Powerplant}$ CaC of ith technology belonging to powerplant
$Technology\ CaC_{i\ TD_{Structures}*}$ CaC of ith technology belonging to $TD_{Structures}*$
$Technology\ CaC_{i\ TD_{Structures}*(Intake)}$ CaC of ith technology belonging to $TD_{Structures}*$ and related to intake
$Technology\ CaC_{i\ TD_{Structures}*(Nozzle)}$ CaC of ith technology belonging to $TD_{Structures}*$ and related to nozzle
TRL_{6-7} Technology Readiness Level 6 to 7
TRL_{7-8} Technology Readiness Level 7 to 8
TRL_{curr_i} current Technology Readiness Level of ith technology belonging to List A
TRL_{Target} target Technology Readiness Level in technology development
$Vehicle\ CaC_{(TRL8)}$ Vehicle Cost at Completion up to Technology Readiness Level 8
$Vehicle\ CaC_{(TRL9)}$ Vehicle Cost at Completion up to Technology Readiness Level 9
WYr_{conv} WYr conversion factor

Acronyms

AC Activity
AD² Advancement Degree of Difficulty
ATLLAS Aerodynamic and Thermal Load Interactions with Lightweight Advanced Materials for High-Speed Flight
ATR Air Turbo Rocket
ATREX Air Turbo Ramjet Engine with eXpander cycle
BB Building Block
CaC Cost at Completion
CER ost Estimation Relationship
CMC Ceramic Matrix Composite
DDTE Design, Development, Test and Evaluation
DMR Dual Mode Ramjet
DOC Direct Operating Cost
EC European Commission
ESA European Space Agency
FAST **20XX** Future High-Altitude High-Speed Transport 20XX
FESTIP Future European Space Transportation Investigations Programme
FY Fiscal Year
H2020 Horizon 2020
HEXAFLY High-Speed Experimental Fly Vehicles
HEXAFLY INT High-Speed Experimental Fly Vehicles International
HIKARI HIgh speed Key technologies for future Air transport - Research & Innovation cooperation scheme
IOC Indirect Operating Cost
IXV Intermediate eXperimental Vehicle
LAPCAT Long-Term Advanced Propulsion Concepts and Technologies
LCC Life Cycle Cost
MC Mission Concept
NASA National Aeronautics and Space Administration
OC Operational Capability
PAC Plasma Assisted Combustion
PBS Product Breakdown Structure
RDTE Research, Development, Test & Evaluation
SH StakeHolder
STRATOFLY Stratospheric Flying Opportunities for High-Speed Propulsive Concepts
TD Technology Domain
TFU Theoretical First Unit
TOC Total Operating Cost
TPS Thermal Protection System
TRIS Technology RoadmappIng Strategy
TRL Technology Readiness Level
US United States
WYr WorkYear

Fig. 1. Flowchart of upgraded TRIS methodology with main objectives.

include hypersonic is presented. However, the goal of that publication was to tailor its application to technologies required for the re-entry phase of a generic hypersonic vehicle, selecting the Intermediate eXperimental Vehicle (IXV) as case study with a specific focus on Thermal Protection System (TPS) technologies. On this basis, to increase the flexibility of the methodology and to widen its applicability to different hypersonic vehicle configurations and missions, TRIS has been thoroughly revised 1) by integrating the technology roadmapping process into conceptual design activity flow, 2), by supporting the definition of activities required to enhance the TRL of each technology and 3) by increasing the accuracy of budget and time resources needed to accomplish technology development. As summarized in Fig. 1, the upgraded TRIS methodology consists now in 5 main steps (Stakeholders' Analysis, Elements' Definition, Prioritization Studies, Planning Definition and Results Evaluation) which will be analysed in Section II. This more rational activity flow facilitates meeting Objective 1. Specifically, Product Breakdown Structure (PBS) and Vehicle Life Cycle Cost (LCC) estimation, usually a result of conceptual design, are exploited to guide, respectively, the derivation of the list of technologies and its characterization in terms of costs. The Elements' Definition has also been improved to support the definition of activities to be completed to increase readiness level of associated technologies (Objective 2). As far as Objective 3 is concerned, both Elements' Definition and Planning Definition algorithms have been involved. In particular, two new semi-empirical models have been included, one in Elements' Definition and the other in Planning Definition, respectively for budget and time resources allocation on TRL Transits, thus increasing the accuracy of time and budget estimation. Moreover, the continuous refinement of the methodology has led to a more flexible and user-friendly activity flow with respect to the original TRIS version [13]. In particular, Stakeholders' Analysis has been placed at the beginning of the overall process to stress its crucial role in steering the decision-making process. As a direct consequence, the prioritization routine has also been improved to guarantee that stakeholders' needs are duly taken account during the technologies' ranking process. All these improvements are detailed in Section II, while Section III thoroughly discusses the application of upgraded TRIS methodology to STRATOFLY. Eventually, Section IV draws main conclusions and highlights envisaged future works.

2. Upgraded TRIS methodology

2.1. Technology roadmapping background

By definition, technology roadmapping methodologies are meant to support the identification of enabling technologies along with the activities required to pursue technology development, operational capabilities and building blocks, on the basis of well-defined performance target [1]. In particular, current roadmapping activities aim at analysing complex systems, knowing the scenario and a few programmatic requirements defined by stakeholders, and at generating an incremental and sustainable technology development plan called roadmap, to be periodically reviewed by stakeholders and experts involved in strategic decisions.

In literature, several roadmapping methodologies already exist [17–22]. As highlighted in Ref. [13], Phaal et al. reports available approaches that are totally or partially based on experts' opinion. Personal and political interests could significantly limit the effectiveness of the overall process, introducing subjective preferences, thus leading to non-technically justified choices. Unlike Phaal et al. works, the approach to technology roadmaps reported in Ref. [22] has a strong technical basis and it is mostly oriented to target for-profit projects, to evaluate the integration of new technologies into already designed products. The authors have decided to upgrade TRIS [13] as reference methodology to support the technology roadmap definition targeted in the H2020 STRATOFLY project. TRIS is complementary to the approach of Phaal et al. as it is a rational, objective, and traceable methodology to generate technology roadmaps to better support strategic decisions in combination with brainstorming sessions with experts' opinions. TRIS shares with [22] the model based and technical structure, but it mainly targets non-profit R&D projects to delineate incremental paths of technology maturation for new missions, products, or capabilities. In combination with traditional methods, it highlights possible incremental paths towards the final goal thanks to the exploitation of common System Engineering tools and processes [23,24] and ad-hoc developed tools. Thanks to the expertise gained in past activities [13,15,16,25–30], TRIS is currently able to derive, track and manage basic roadmap elements in the aerospace domain and to optimize their relationship in a decision-making process. As intended in TRIS, a technology roadmap is the result of complex and strictly interwoven activities aiming at identifying, prioritizing, selecting and combining elements belonging to the following categories (also known as technology roadmap pillars). Specifically, 1) Operational Capabilities (OCs) are high-level functions responding to a mission statement (e.g., the capability to perform antipodal flights at Mach 8); 2) Technologies are considered "the technical know-how that is required for the design, manufacture and test of a space product, including all related processes" [31] (for sake of clarity, a set of technologies including the "know-how relevant to a technical area" [31] constitute a Technology Domain (TD), for example, Propulsion, Structures and Mechanisms, and Thermal are TDs); 3) Building Blocks (BBs) are physical elements that include several technologies

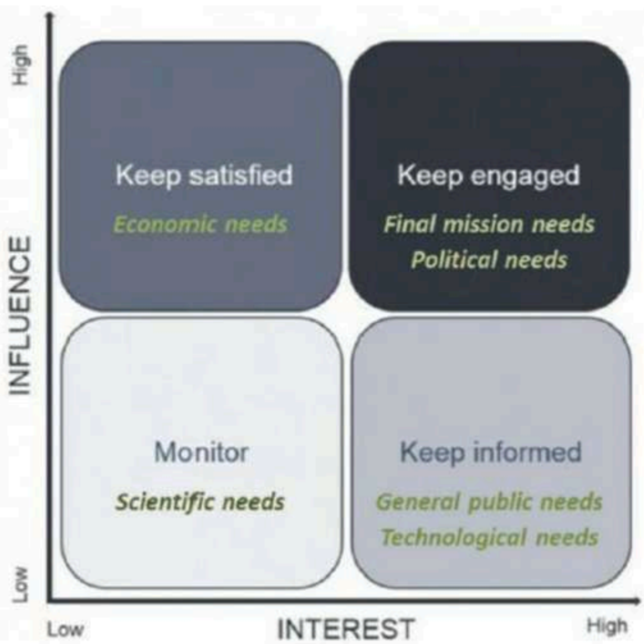


Fig. 2. Strategy grid.

combined together to achieve certain functions (OCs), e.g., a technology flight demonstrator and 4) Mission Concepts (MCs) or Activities (ACs) are a set of research, development and test activities, demonstrative missions or real flights requested to increase the readiness level of each technology or BB, e.g., wind tunnel test (AC) and flight mission performed by a demonstrator (MC).

TRIS has already proven to be suitable for hypersonic and re-entry space transportation systems, supporting ESA's technology initiatives within this field [13] in addition to space exploration domain [14–16, 25]. However, as anticipated in the introduction, the goal of [13] was to verify the potential applicability of the methodology to deal with technologies required for the re-entry phase of a generic hypersonic vehicle. In that context, as mentioned, the IXV was selected as case study with a specific focus on TPS technologies. On this basis, to increase the flexibility of the methodology and to widen its applicability to different hypersonic vehicle configurations and missions, the results of the update of TRIS methodology to support the technology roadmap definition aimed in the H2020 STRATOFLY project are presented. Specifically, three main objectives are here targeted: 1) to integrate the technology roadmapping process into conceptual design activity flow, 2) to support the definition of activities required to enhance the TRL of each technology and 3) to increase the accuracy of budget and time resources needed to accomplish technology development. Therefore, the following subsections describe step by step the upgraded TRIS methodology focusing on the elements of novelty introduced to meet the three main objectives mentioned above (Fig. 1).

2.2. *TRIS steps revision: stakeholders' analysis*

This step is an element of novelty for the methodology: comparing Fig. 1 with the original TRIS methodology flowchart reported in Ref. [13], the process starts from a Stakeholders' Analysis, which is now specified as an independent step considering its crucial role in any decision-making process. Indeed, it is essential to identify from the very beginning of roadmapping activities all the entities involved in the process, specifying their role(s) and predicting their impact on the final decision [32,33]. According to Ref. [34], all the actors shall be categorized depending on their role (Sponsors, Operators, End-users and Customers) and characterized according to their main areas of interest in the analysis (final mission needs, political needs, general public needs, economic needs, scientific needs, or technological needs). Depending on the category and the area of interest which each stakeholder belongs to, it is possible to predict the influence and the interest of each actor. The association between category, area of interest, stakeholder influence and interest can be predicted thanks to the exploitation of a Strategy Grid. Based on [35], the Strategy Grid here proposed and reported in Fig. 2 organizes stakeholders in 4 main areas of influence/interest. In particular, stakeholders expressing scientific needs are usually interested in monitoring the activity, thus both their interest and influence are considered low. Stakeholders expressing public needs or technological needs can be more involved in the activities with a higher interest with respect to the previous category. However, the level of influence of these stakeholders remains low. On the contrary, stakeholders expressing economic needs (such as funding authorities) are expected to have a higher influence on project decisions, while stakeholders with political needs or involved into the final mission results are associated to highest levels of interest and influence. Practically, the goal of Stakeholders' Analysis is to collect all stakeholders' expectations in form of parameters to be monitored and exploited during the decision-making process. In addition, considering that these parameters will be used during Prioritization Studies, it is also essential that each stakeholder associates a prioritization order (ascending or descending) to each defined parameter to express a criterion as in Eq. (1):

$$K_{SG_i} \cdot K_{Cij} \cdot (\text{Parameter} + \text{in Ascending/Descending Order}) \tag{1}$$

It is clear that depending on stakeholder position on the Strategy Grid, criteria expressed by any stakeholder can be properly weighted (K_{SG_i}) to mirror the influence of the stakeholder itself on the selection process. In case of single SH, K_{SG_i} is set to 1. Complementary, if a stakeholder expresses more than a criterion, it is important to identify a priority/order for the application of the criteria. This is mathematically formalized in K_{Cij} (Eq. (1)), which represents an additional weighting factor set to 1 in case of single criterion or customizable depending on the case of several criteria.

2.3. *TRIS steps revision: elements' definition*

Moving towards step 2 of the updated TRIS methodology, lists of elements for each pillar (i.e., MCs/ACs, OCs, BBs and technologies) relevant to the case study are defined or retrieved from a database, if available. In addition, each element is characterized with properties reflecting the parameters asked by stakeholders during the previous step. Compared to the former TRIS flowchart [13], Elements' Definition phase compacts the previously named "Roadmap elements definition and characterization", "Applicability analysis" and "Sensitivity analysis", by rationalizing the process. As reported in Fig. 1, this step presents elements of novelty: 1) on one side, the link with the conceptual design methodology has proved to be beneficial for the definition of list of technologies (thanks to the exploitation of a PBS) (Objective 1) and, on the other side, the availability of a LCC estimation has allowed to increase the accuracy of the estimation of necessary budget resources (Objective 3); 2) guidelines for the definition of a list of ACs and MCs to pursue the claimed technology development.

2.3.1. *Improvements to technologies and BBs list derivation*

Specifically, as far as technologies' list is concerned, a structured database with lists of hypersonic technologies is not publicly available. Therefore, this paper suggests a strategy to overcome this lack of information, creating a link between this step of the methodology and conceptual design activities. Specifically, following the guidelines provided by NASA [24] and the most up-to-date conceptual design methodology for high-speed vehicles [33,36–39], the PBS can be used as guideline. The PBS should be detailed enough to allow a straightforward derivation of technologies' list and BBs list, describing vehicle elements'

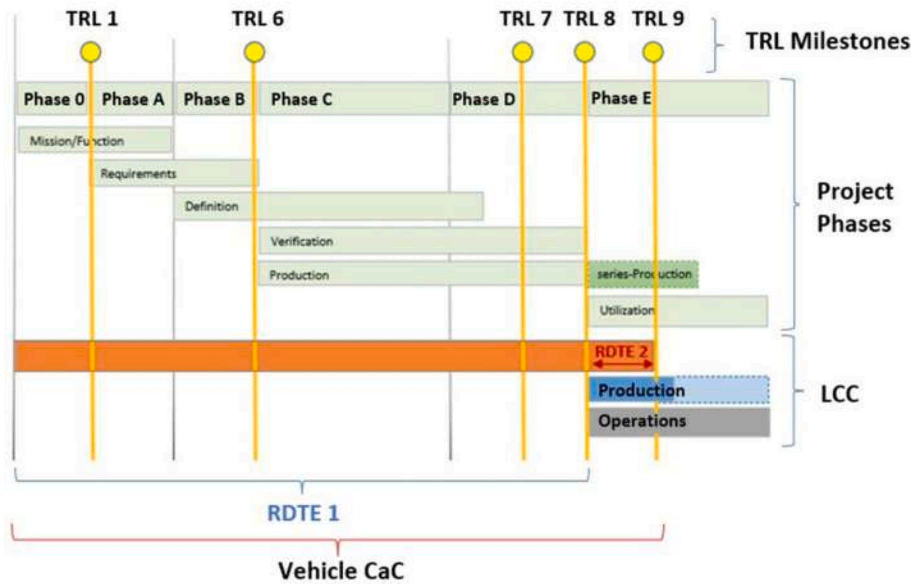


Fig. 3. Location of TRL Milestones on Project Phases for hypersonic derived from original ESA subdivision.

up to component or, if possible, to sub-component level. The exploitation of a PBS can also guarantee the derivation, in a logical way, of the links existing between technologies and BBs (at different hierarchical level).

2.3.2. Improvement to technologies' CaC estimation

The connection with the activities of conceptual design has proved to be beneficial to improve the accuracy in the estimation of necessary budget resources, also defined as technologies' Cost at Completion (CaC). CaC is the cost to be sustained to increase the TRL from 1 up to TRL 9. Values of technologies' CaC can be retrieved from database (e.g., ESA space exploration database [40]), but historical data for hypersonic case studies are not available [41]. Therefore, the algorithm suggested by authors in this subsection exploits the results of Vehicle LCC estimations, usually carried out in conceptual design, as input for technologies' CaC estimation. To move from Vehicle LCC to technologies' CaC, it is necessary to estimate Vehicle CaC, which in turn can be evaluated knowing the Vehicle LLC, and the cost items allocated onto PBS as reported in Eq. (2).

$$Technology\ CaC_i = f\{Vehicle\ CaC\ [g(Vehicle\ LCC)],\ PBS\ Cost\ Items\} \lim_{x \to \infty} \tag{2}$$

where *Technology* CaC_i is CaC of ith technology.

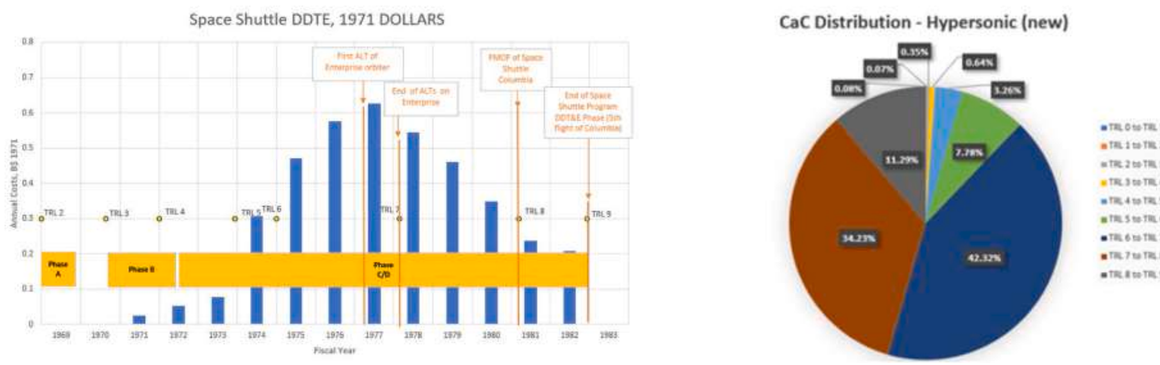
Considering that, in literature, suggestions for hypersonic Vehicle CaC are not directly available, a formulation based on Vehicle LCC (usually available from conceptual design) and exploiting the definition of CaC is disclosed. The formalization of the link between Vehicle CaC and Vehicle LCC is at the basis of the formulation. On one side, LCC analysis carried out in conceptual design includes a set of Cost Estimation Relationships (CERs) to estimate Research, Development, Test & Evaluation (RDTE) cost, Theoretical First Unit (TFU) Production cost and Total Operating Cost (TOC) as a function of main vehicle characteristics (such as dry mass) [42–44]. On the other side, according to its definition, Vehicle CaC sums up all the cost incurred in each project phase, from Phase 0 up to Phase E. Therefore, to move from Vehicle LCC to Vehicle CaC, a correlation between Project Phases and main LCC items (i.e., RDTE, Production, etc.) is necessary (Fig. 3). In detail, in line with ESA Project Phases definition [45], the link between main Project Activities (i.e., Mission/Function (definition), Requirements (definition), etc.) and Project Phases (i.e., Phase 0, Phase A, etc.) has been derived. For example, Mission/Function (definition) activity is performed during Phases 0 and A, Moreover [45], contains the indication of major TRL milestones (i.e., from TRL6 on) and their association to Project Phases. Fig. 3 exploits indications and definitions available in Ref. [45] and suggests a way to map Project Activities onto LCC items. In detail, specifically considering hypersonic vehicles, RDTE costs are expected to cover Mission/Function (definition), Requirements (definition), (System) Definition, Verification, Production (of flight demonstrators), and Utilization (with flight demonstration accomplishment), spanning all TRL milestones up to TRL 9, when development phase officially ends. In this context, it is worth to notice that Production and Utilization phases reported in original ESA subdivision are not specifically referred to a hypersonic vehicle, in which series-production phase has to be included and it is usually carried out in parallel to flight operations.

For sake of clarity, the first portion of CaC up to TRL 8 is labelled as "RDTE 1" (Fig. 3), while the CaC between TRL8 and TRL9 is labelled as "RDTE 2". In parallel, from TRL8 onwards, costs related to the production of the TFU and initial operations [45] costs have to be considered. Therefore, Vehicle CaC up to TRL 9 can be expressed as follows:

$$Vehicle\ CaC_{(TRL9)} = Vehicle\ RDTE + Vehicle\ TFU\ Production + Initial\ Operations \tag{3}$$

where *Vehicle* $CaC_{(TRL9)}$ is Vehicle CaC up to TRL 9.

It is worth highlighting that, differently from Vehicle CaC, technologies' CaC assessment is effectively applicable up to TRL8 instead of TRL9, considering that, at that stage, all technologies are physically integrated onto the actual flight vehicle. In account of this, only the costs incurred up to TRL8, i.e., RDTE 1 component, are allocated onto technologies. Please, note that Fig. 3 clarifies that Vehicle CaC up to TRL8



(a) (b)

Fig. 4. (a) Space Shuttle DDTE subdivision and TRL milestones achieved and (b) newly derived Vehicle CaC distribution on TRL transits for hypersonic transportation systems.

(Vehicle $CaC_{(TRL8)}$) is equal to a percentage of RDTE, i.e., RDTE 1, which is also referred as Vehicle CaC up to TRL8 (Eq. (4)).

$$RDTE\ 1 = Vehicle\ CaC_{(TRL8)} = K_1 \cdot Vehicle\ CaC_{(TRL9)} \tag{4}$$

where $Vehicle\ CaC_{(TRL8)}$ is Vehicle CaC up to TRL 8 and K_1 represents the percentage of Vehicle CaC up to TRL 8.

Then, using equations for RDTE cost, TFU Production cost and TOC from Ref. [42], Eq. (4) might be re-arranged as:

$$\begin{aligned} &Vehicle\ CaC_{(TRL8)} = \\ &K_1 \cdot \left(f_0 \left(H_{VA} + \sum_{i=1}^{n_E} H_{Ei} \right) f_6 f_7 + F_V + \sum_{j}^{n_e} F_{E_j} f_{4_j} \right) \right) \cdot WYr_{conv} + \\ &n_{init.\ ops} \left(\frac{DOC_{Fuel}}{Flight} + \frac{DOC_C}{Flight} + \frac{DOC_I}{Flight} + \frac{DOC_D}{Flight} + \frac{DOC_M}{Flight} + \frac{IOC}{Flight} \right) \end{aligned} \tag{5}$$

where:

f_0 is Systems engineering integration factor for development.

H_{VA} is RDTE cost for high-speed advanced aircraft in WorkYear [WYr].

n_E is the number of engine types installed (e.g., turbojet, ramjet or combined cycle engine).

H_{Ei} is RDTE of engine (of a specified type).

f_6 represents deviation from optimal development schedule (delay factor).

f_7 is program organization factor.

$f_0(H_{VA} + \sum_{i=1}^{n_E} H_{Ei}) f_6 f_7$ is total vehicle (including engines) RDTE cost in WYr.

F_V is TFU Production cost for high-speed advanced aircraft in WorkYear [WYr].

n_e is the number of engines of a specified type installed on the vehicle.

f_{4_j} is the learning curve factor associated to the jth engine of a specified type produced.

$\sum_{j}^{n_e} F_{E_j} f_{4_j}$ is total engines Production cost for engines installed on vehicle TFU.

WYr_{conv} is the WYr conversion factor fom WYr to € for Fiscal Year (FY) 2020 (see Ref. [42] for further details).

$n_{init.\ ops}$ is the number of flights assumed for initial operations (e.g., 5 flights for Space Shuttle).

$\frac{DOC_{Fuel}}{Flight}$ is the Direct Operating Cost (DOC) for fuel per flight in € FY2020.

$\frac{DOC_C}{Flight}$ is the DOC for crew per flight in € FY2020.

$\frac{DOC_I}{Flight}$ is the DOC for insurance per flight in € FY 2020.

$\frac{DOC_D}{Flight}$ is the DOC for depreciation per flight in € FY2020.

$\frac{DOC_M}{Flight}$ is the DOC for maintenance per flight in € FY 2020.

$\frac{IOC}{Flight}$ is the Indirect Operating Cost (IOC) per flight in € FY 2020.

Detailed expressions for H_{VA}, H_{Ei}, F_V, F_{E_j}, DOC and IOC contributions can be found in Ref. [42].

The estimation of K_1 (Eq. (5)) for hypersonic vehicle requires to understand the distribution of Vehicle CaC on TRL transits. In Ref. [27] a first attempt of CaC distribution on TRL transits for hypersonic and re-entry space transportation systems has been performed mainly thanks to experts' opinion. In this context, to validate the model in Ref. [27] with real historical cost data, a new semi-empirical model is suggested. The semi-empirical model is based on Space Shuttle, the only reusable hypersonic system for which complete cost data are available. Fig. 4 (a) graphically depicts the annual costs for Design, Development, Test and Evaluation (DDTE) for Space Shuttle spent from 1971 to 1982 [46]. Then, in order to distribute available costs on TRL transits, TRL milestones have been placed along the timeline of Space Shuttle development program as shown in Fig. 4. Please, note that the link with TRL milestones is not provided directly in Ref. [46], but it has been added by the authors following the guidelines from Ref. [45].

The association of TRL Milestones along the timeline allows to suggest a new Vehicle CaC distribution on TRL transits to be compared with the original CaC distribution from Ref. [27]. The final CaC breakdown, reported in Fig. 4 (b) is in line with the original and it confirms that great part of development costs of hypersonic are related to TRL transits from 6 to 7 and from 7 to 8, when flight demonstrators are designed, produced and tested. From this analysis a value of 0.8871 for K_1 (Eq. (5)) can be derived (related to TRL transits from 1 to 8).

Once Vehicle CaC is estimated, in order to derive the CaC of each technology, the exploitation of PBS is suggested. Indeed, from Eq. (2), technologies' CaC is function of both Vehicle CaC and its allocation onto PBS. At this purpose, the correspondence between PBS elements and TDs, which technologies belong to, shall be assessed, so that each portion in PBS costs breakdown is related to the jth TD (K_{TDj}). PBS costs allocation can be derived from existing commercial tools, like for example the True Planning software by Price Systems. In particular, considering that RDTE cost (specifically, RDTE 1 contribution in Fig. 3) is sufficient to determine technologies' CaC up to TRL8, only RDTE costs allocation onto PBS is needed. An example of numerical values for K_{TDj} for a hypersonic vehicle is reported in Ref. [42]. Once K_{TDj} has been identified, it is necessary to proceed with the final costs' allocation onto technologies. In particular, depending on data availability, one of the following strategies can be pursued:

1. If PBS costs breakdown is available at component level (for example, from Price True Planning software), the cost of associated technologies is equal to component cost divided by the number of

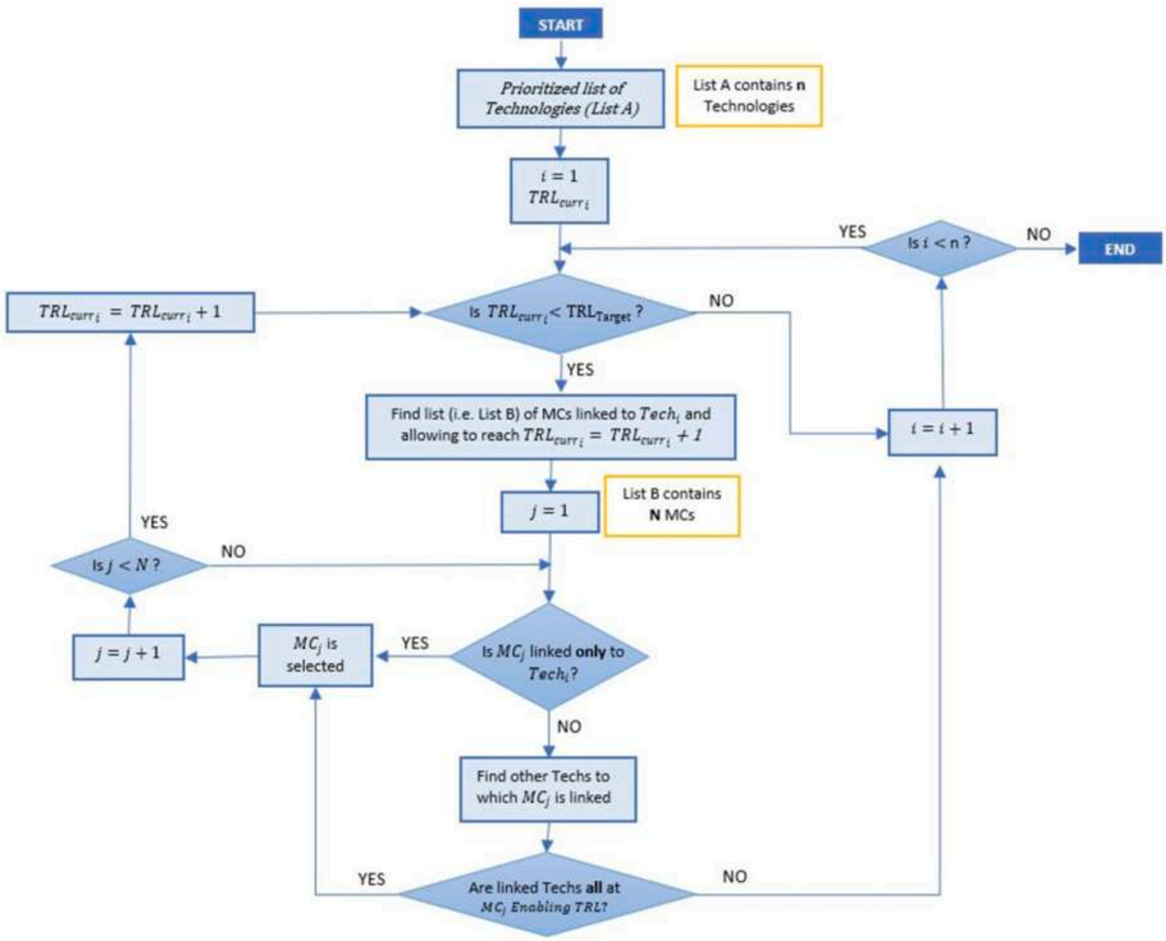


Fig. 5. New Planning Definition flowchart.

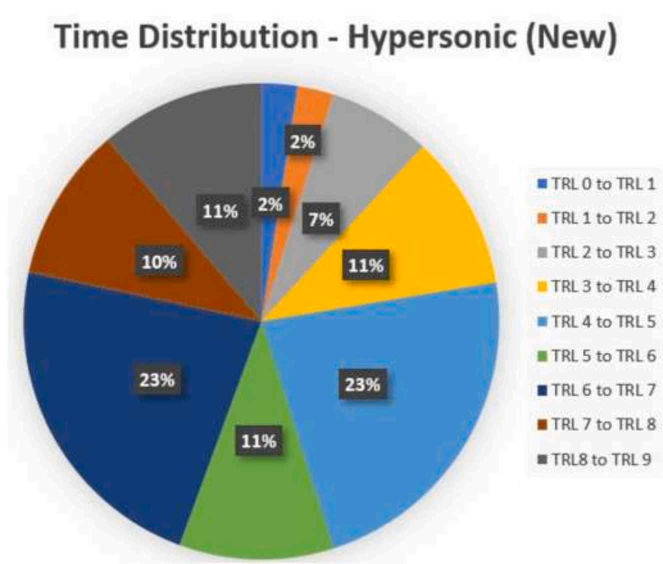


Fig. 6. Newly derived time distribution applicable to hypersonic transportation systems.

technologies linked to that component. In case information about the relative importance (in terms of costs) of technologies associated to the same component is available, proper weight factors might be introduced ($K_{Tech\ i}$), associating more importance (i.e., cost) to certain technologies than others;

2. If PBS costs breakdown is not available at component level, an ad-hoc weighting strategy shall be adopted.

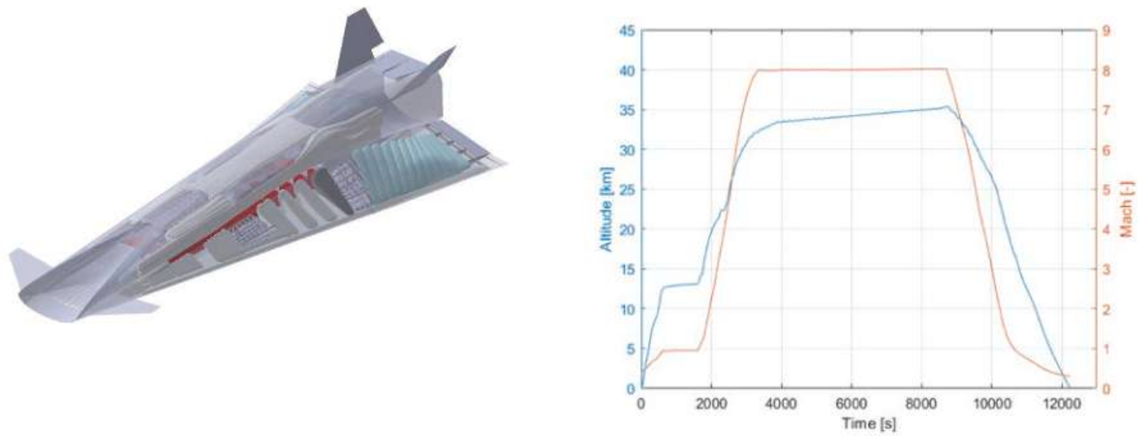
To summarize, the CaC of ith technology belonging to jth TD ($Technology\ CaC_{ij}$) can be evaluated as a function of $Vehicle\ CaC_{(TRL8)}$ as in Eq. (6):

$$Technology\ CaC_{ij} = K_{Tech\ i} \cdot K_{TDj} \cdot Vehicle\ CaC_{(TRL8)} \tag{6}$$

where $K_{Tech\ i}$ represents cost fraction associated the ith technology relatively to other technologies in the same TD.

2.3.3. Improvements to MCs and ACs list derivation

As introduced at the beginning of the section, among the novelties introduced in Elements' Definition step there are also guidelines for the definition of a list of ACs and MCs to pursue the claimed technology development in case they cannot be directly retrieved from databases. In particular, a preliminary list of ACs and MCs might be derived from TRL definitions provided by ESA in Ref. [45]. This list is generic and applicable to any aerospace-related initiative and shall be customized to better fit the case study. For hypersonic transportation systems, original ESA list of ACs can be specialized looking at the real activities carried out in Europe and outside to enhance TRL of hypersonic technologies. Moreover, considering that a technology roadmap for future hypersonic transportation systems may envisage flight demonstrations, it is also important to include into the list of ACs and MCs flight demo missions. Specifically, basing on the TRL definitions provided in Ref. [45] and the



(a) (b)

Fig. 7. (a) STRATOFLY MR3 external configuration and (b) reference trajectory.

Fig. 8. STRATOFLY MR3 PBS.

hypersonic flight demonstrations envisaged by Ref. [47], the following three main demo missions can be suggested for a Mach 8 cruiser:

- Flight Demo 1a: 6–10 Small Scale Vehicle(s) (1/10 of full-scale cruiser), recoverable (not reusable) allowing to characterize

Table 1
List of technologies considered during STRATOFLY roadmapping exercise.

Technology ID	Technology Name	Parameters of SH defined Criteria		
		AD^2	Starting TRL	CaC [M€ FY2020]
1	Low Speed Intake Ramp Technology	4	6	350.27
2	Low Speed Intake Duct Technology	4	6	350.27
3	High Speed Intake Technology	5	4	350.27
4	2D Nozzle Technology	1	7	100.51
5	3D Nozzle Technology	5	4	100.51
6	ATR Exhaust Duct Technology	5	6	100.51
7	ATR Variable Throat Technology	5	6	100.51
8	ATR Fan Technology	7	6	620.15
9	ATR Turbines Technology	2	7	413.43
10	ATR Combustor Technology	5	6	620.15
11	Engine Controls Technology	5	6	413.43
12	DMR Injection Struts Technology	3	6	413.43
13	Scramjet Combustor Technology	6	6	413.43
14	Ramjet-Scramjet Transition Technology	6	4	620.15
15	Plasma Assisted Combustion (PAC) Technology	6	1	124.03
16	Isolator Technology	4	4	620.15
17	ATR Pumps Technology	2	6	413.43
18	Intake Ramps Actuators Technology	6	4	289.40
19	Variable Throat Actuators Technology	6	6	289.40
20	Engine Cooled Materials (CMC)	7	6	620.15
21	Engine Cooled Materials (Metals)	7	6	620.15
22	Engine Uncooled Materials	5	6	413.43

Table 2
Summary of LCC data for STRATOFLY MR3.

Cost Item	Cost [M€ FY 2020]
Vehicle RDTE	26,481
Vehicle TFU Production	1485
Initial Operations (5 Flights)	5.06
Vehicle CaC (up to TRL 9)	27,971
RDTE 1 (or Vehicle CaC (up to TRL 8))	23,491

Table 3
$K_{Tech\ i_{Powerplant}}$ for propulsive technologies.

Reference PBS Element	Powerplant Technology	Estimated RDTE Effort Level	Level Weight	$K_{Tech\ i_{Powerplant}}$ [%]
ATR	ATR Fan Technology	MODERATE	1.5	9%
	ATR Turbines Technology	LOW-MODERATE	1	6%
	ATR Combustor Technology	MODERATE	1.5	9%
	ATR Pumps Technology	LOW-MODERATE	1	6%
DMR	DMR Injection Struts Technology	LOW-MODERATE	1	6%
	Scramjet Combustor Technology	LOW-MODERATE	1	6%
	Ramjet-Scramjet Transition Technology	MODERATE	1.5	9%
	PAC Technology	VERY LOW	0.3	2%
Isolator	Isolator Technology	MODERATE	1.5	9%
Engine Controls	Engine Controls Technology	LOW-MODERATE	1	6%
Actuators	Intake Ramps Actuators Technology	LOW	0.7	4%
	Variable Throat Actuators Technology	LOW	0.7	4%
Engine Materials	Engine Cooled Materials (CMC)	MODERATE	1.5	9%
	Engine Cooled Materials (Metals)	MODERATE	1.5	9%
	Engine Uncooled Materials	LOW-MODERATE	1	6%

hypersonic environment at different flight conditions in the Mach range 3–8;

- Flight Demo 1b: 3 Mid Scale reusable vehicles (1/3 scale engine) able to perform 6–9 flight tests in the Mach range 3–8;
- 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).

Flight Demo 1a and 1b can be associated to an overall TRL transit from TRL 6 to 7, while Flight demo 2 can allow to move from TRL 7 to 8.

Eventually, in line with the characterization of technologies' list, ACs and MCs shall be characterized as well. In this case, the parameters required are mainly Enabling TRL and End TRL, where the former is the TRL that all technologies linked to that AC or MC shall reach to enable it, while the latter is the TRL achieved thanks to the specific AC or MC.

2.4. TRIS steps revision: Prioritization Studies

The third step of updated TRIS methodology consist in Prioritization Study in line with the original TRIS activity flow [13]. However, the routines laying behind this step have been completely revised to better represent the stakeholders' requests into the prioritization process. In the original TRIS methodology, a predefined set of figures of merit were at the basis of the prioritization of technologies, only partially accounting for the needs identified by the different stakeholders. Conversely, this new Prioritization Studies step is based on a more flexible algorithm which exploits trade-off analyses [24]. In this new process, all criteria derived from Stakeholders' Analysis can be used as figures of merit, thus contributing to the final technologies' ranking depending on the related stakeholder influence/interest.

From Elements' Definition step, for each identified technology there is a list of associated ACs and MCs to support all the requested TRL Transits. It is therefore important to identify strategies to select the most promising alternative AC or MC to accomplish the specific TRL Transit. At this purpose, trade-off analysis can be exploited as well using proper figures of merit, such as AC/MC cost, number of technologies linked, number of BBs linked, etc. This approach is different from the original strategy [13], where the prioritization of the entire list of MCs and ACs was carried out in parallel to technologies prioritization independently from the link existing between activities and technologies. In the original methodology, the matching of MCs and ACs with technologies occurred during the Planning Definition phase, while this activity is currently anticipated during Prioritization Studies.

2.5. TRIS steps revision: Planning definition

The Planning Definition step was thoroughly discussed in Ref. [13]. In the original algorithm, the already ranked lists of technologies and missions were combined together mainly checking the Enabling TRL of MCs and ACs and considering budget availability. The main drawback of the original Planning Definition routine lies in the fact that technologies were associated to MCs one by one neglecting the possibility to increase the TRL of a set of technologies with a single AC or MC. The integration of technologies is a crucial aspect of hypersonic systems and the possibility of reproducing it during the Planning Definition phase is central to suggest economically viable technology development paths. Therefore, a new Planning Definition routine is here proposed and graphically summarized in Fig. 5.

To complete the Planning Definition, the ordered list of MCs has to be properly distributed on a timeline. At this purpose, a new semi-empirical model for time resources allocation is proposed to improve the Planning Definition algorithm, thus increasing the accuracy of time allocation. In literature, there is no indication to estimate the duration of TRL transits for technologies of a hypersonic transportation system. Therefore, a specific time breakdown is suggested (Fig. 6), following the approach adopted for Space Exploration in Ref. [27] and exploiting available time data from FESTIP programme [48] (a European program for hypersonic technology development of the nineties) and actual from Sänger project [49].

The time breakdown provided in Fig. 6 is used to define a

Table 4
List of MCs to TRL 9 for PAC technology.

AC/MC Name	Enabling TRL	End TRL
Expression of basic principles for intended use of PAC Technology	0	0
Identification of potential applications of PAC Technology	0	1
Preliminary design of Scramjet Combustor with PAC Technology, providing understanding of how the basic principles are used	1	1
Formulation of potential application of PAC Technology	1	1
General definition of performance requirements for PAC Technology	1	2
Scramjet Combustor Design including PAC Technology	2	2
Scramjet Combustor Numerical Analysis/Simulation including PAC Technology	2	3
Design of Scramjet Combustor model(s) with PAC Technology for combustion test (not yet integrated into engine model)	3	3
Fabrication of Scramjet Combustor model(s) with PAC Technology for combustion test(s)	3	3
Combustion test(s) of Scramjet Combustor model(s) with PAC Technology	3	4
Design of Scramjet Combustor model to be integrated into DMR engine model	4	4
Fabrication of Scramjet Combustor model(s) to be integrated into DMR engine model(s)	4	4
Test of Scramjet Combustor model before integration into DMR engine model(s)	4	5
Integration of DMR engine model elements	5	5
Sea-level firing test(s) of DMR engine model	5	5
Design of DMR engine model to be integrated into propulsion plant model	5	5
Fabrication of DMR engine model(s) to be integrated into propulsion plant model(s)	5	5
Sea-level firing test(s) of propulsion plant model(s)	5	6
Design of DMR engine model to be integrated into Small Scale Flight Demonstrator	6	6
Fabrication of DMR engine model(s) to be integrated into Small Scale Flight Demonstrator(s)	6	6
Flight test(s) of Small-Scale Flight Demonstrator(s)	6	6
Design of DMR engine model to be integrated into Mid Scale Flight Demonstrator	6	6
Fabrication of DMR engine model(s) to be integrated into Mid Scale Flight Demonstrator(s)	6	6
Flight test(s) of Mid Scale Flight Demonstrator(s)	6	7
Design of DMR engine model to be integrated into Near Full Scale Flight Demonstrator	7	7
Fabrication of DMR engine model(s) to be integrated into Near Full Scale Flight Demonstrator(s)	7	7
Flight test(s) of Near Full Scale Flight Demonstrator(s)	7	8
STRATOFLY MR3 Mission(s)	8	9

preliminary development timeline for each technology that has to be then refined with the actual list of ACs and MCs to be performed to cover each TRL transit. It is worth noticing that, in case an AC or MC is linked to more than a technology, the starting date of the AC/MC shall be fixed after all the related technologies have already reached the minimum TRL requested by the AC/MC itself (i.e., Enabling TRL). This activity allows for the definition of a final timeline per each technology. Lastly, merging the final timeline derived for each technology with the ordered and linked list of ACs/MCs previously obtained (by applying the activity flow in Fig. 5), it is possible to define a final planning and to generate the incremental path for the maturation of each technology. The expected graphical outcomes consist in two different Gantt Charts, one reporting the time and budget allocation on TRL Transits for each selected technology together with TRL Milestones elicitation; the other one focusing on the ordered ACs/MCs list along the same timeline. This dual visualization is possible thanks to the well-established link between techs and ACs/MCs.

2.6. TRIS steps revision: Results evaluation

The Results Evaluation step can be considered as a synthesis of the overall roadmapping activities carried out in the previous steps. This step was already foreseen in the original TRIS version [13] to support the analysis of different out-of-nominal scenarios and to perform sensitivity analysis to understand the impact of stakeholders' expectations onto the final roadmap. This allows also to perform a risk analysis, to associate each technically viable roadmap to a level of risk, depending on the foreseeable difficulties in reaching the TRL target. Likewise, the results of different technology roadmaps (either as mission or product) can be compared on the basis of the expected revenues, which can be expressed as stakeholders' criteria, thus analysing the impact of stakeholders' expectations onto the final roadmap. A possible upgrade to this final step is currently under investigation and can consist in providing a wider set of results' visualization, exploiting all information available at the end of the process, including the links between the different elements.

3. Upgraded TRIS methodology application to STRATOFLY

This Section aims at describing the application of the upgraded TRIS methodology in the framework of the H2020 STRATOFLY project to meet one of its main goal, i.e., assessing the potential of a high-speed transport vehicle to reach TRL 6 by 2035 with respect to key technological, societal and economical aspects. A after a brief description of the reference vehicle and mission, the upgraded TRIS methodology is applied step by step, specifically focusing on propulsive technologies.

Please notice that all costs data for this case study are reported for the Fiscal Year 2020 (FY2020), as this was the conclusive year of the H2020 STRATOFLY Project. However, to update these values to FY 2021, the reader shall simply multiply the values of FY 2020 by 1.047.

3.1. Case study: STRATOFLY MR3 propulsive technologies

Benefitting from the heritage of previous European projects and selecting the LAPCAT MR2.4 (Mach 8, waverider configuration) vehicle and mission as reference [4], the H2020 STRATOFLY project aims at further investigating the vehicle and mission concepts through dedicated multi-disciplinary design methodologies, highly integrated subsystems design, high-fidelity simulations, and test campaigns [11]. In addition, socio-economic and environmentally sustainable aspects are specifically investigated [12]. Making benefit of the achievements of previous EC funded projects, a new vehicle concept, named STRATOFLY MR3, has been further investigated and improved. Specifically, the waverider configuration suggested for the STRATOFLY MR3 concept (Fig. 7 (a)) is equipped with a dorsal mounted propulsive system completely embedded into the airframe. The MR3 propulsion plant, inherited from the MR2.4 vehicle, embodies six Air Turbo-Rocket (ATR) engines to propel the vehicle from idle to the supersonic speed and a Dual-Mode Ramjet (DMR) engine to satisfy the requirements for hypersonic acceleration and cruise condition at Mach 8. These two types of engines co-operate to accelerate and propel the vehicle for a wide speed range including the supersonic-to-hypersonic transition (Fig. 7 (b)). Since the previous projects, the crucial role of the propulsive subsystem has motivated the search for highly performant and integrated technologies, whose low readiness level may jeopardize all the research efforts taken so far. Therefore, the H2020 STRATOFLY goal of assessing the potential of a high-speed transport vehicle to reach TRL 6 by 2035, coincides with verifying that the selected propulsive technologies may reach that TRL target in the specified timeframe.

3.2. Step 1: stakeholders' analysis

Even if several Stakeholders are involved in the H2020 STRATOFLY project, it is undoubtful that EC plays the most impacting role, in view of

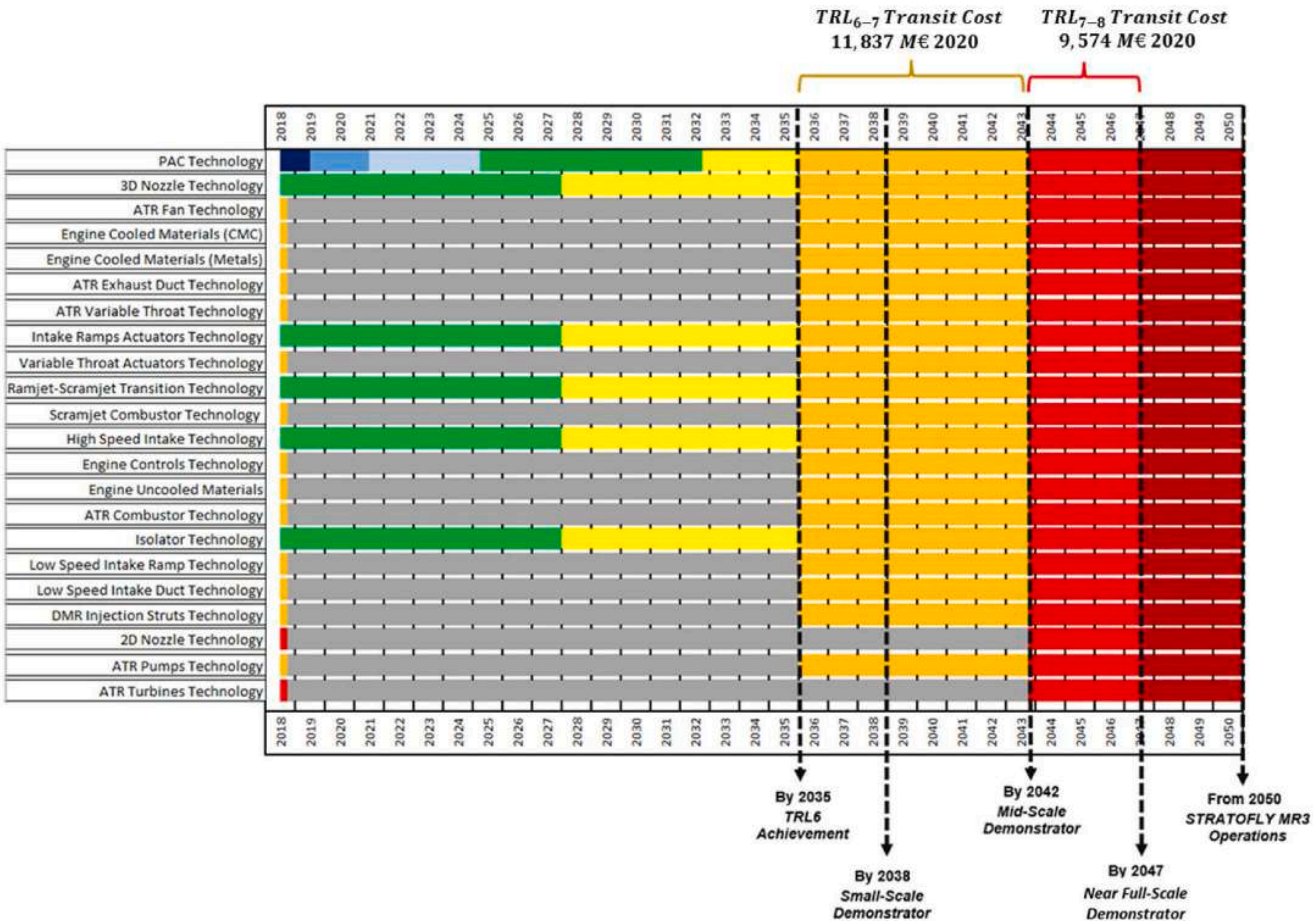


Fig. 9. Technology roadmap for STRATOFLY propulsive technologies.

its political and economic interests in the initiative. This is also emerging from the application of the Strategy Grid (see Fig. 2), where the stakeholder EC can be located in the area with the highest interest/influence. The analysis of EC needs, as unique stakeholder (i.e., $K_{SG} = 1$ in Eq. (1)), brings to the identification of a set of interesting criteria to be then used during the prioritization study. Specifically, in line with EC research policies, the H2020 framework supports high-risk/high-gain technology development initiatives. In addition, the focus onto breakthrough technologies leads to a focus on low-TRL. Finally, budget constraints cannot be neglected, thus EC recommends optimizing budget resources, maximizing the results by minimizing the expenditures. These specific needs can be translated into the following criteria (with related weighting factors according to Eq. (1)):

- Advancement Degree of Difficulty (AD^2) in Descending Order: following the nine-levels definition of AD^2 from Ref. [47], it expresses the risk encountered in technology development. Therefore, according to this first criterion, the list of technologies shall be ranked starting from those associated to higher risk with the aim to define, in a conservative way, the most critical technology development path ($K_{CAD2} = 0.5$);
- Starting TRL in Ascending Order: the list of technologies shall be ranked starting from those at lower TRL to level out the TRL of all technologies and enable the introduction of proper flight demonstrators ($K_{CTRL} = 0.33$);
- 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 ($K_{CCaC} = 0.17$).

In addition, during this step it is important to set the roadmap target, which is mainly defined in terms of Target TRL and reference timeframe. The STRATOFLY Project already suggests an intermediate TRL6 Milestone to be reached by 2035, however it is also important to identify when technology development shall be completed. Specifically, 2050 is set as Target Date for TRL 9 Milestone achievement, in line with the outcome of previous roadmapping analyses for hypersonic transportation systems performed in the framework of HIKARI project [51]. In that context, a preliminary technology development schedule has been proposed for the major TDs but without analysing specific technologies. In addition, according to HIKARI results, flight demonstration of the integrated system would occur around 2045. It can be here anticipated that the 2050 hypothesis has proved to be feasible to accommodate the intermediate TRL 6 milestone in 2035.

3.3. Elements' definition

As far as step 2 is concerned, the lists of elements required during the roadmapping process are defined, with specific focus on technologies and ACs/MCs. For the present application, considering the lack of retrieving data from already existing databases, the following subsections exploits the suggestions reported in Section C, where the link with conceptual design is exploited to define and characterize the list of technologies, while guidelines from Space Agencies support the definition of ACs/MCs list.

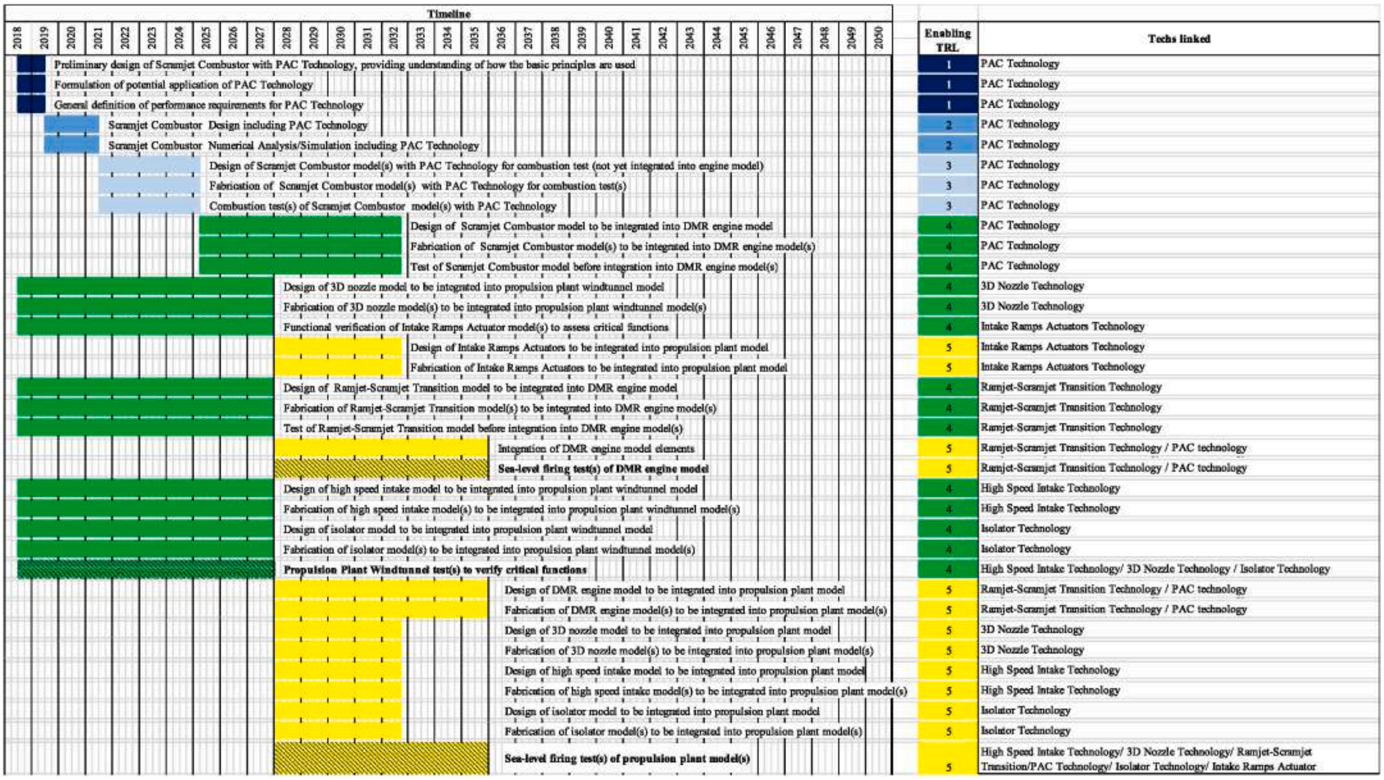


Fig. 10. Example of timeline for low/medium TRL ACs linked to STRATOFLY technologies.

3.3.1. Technologies

Benefitting of the conceptual design activities caried out in STRATOFLY [11], the PBS in Fig. 8 has been used as baseline for the derivation of the list of all technologies belonging to Propulsion TD. The list is reported in Table 1. Of course, the interaction with experts in the project has been beneficial for both the finalization of the list as well as for the characterization of its elements. In fact, data required for the following technology prioritization, i.e., the criteria identified during Stakeholders' Analysis, have been associated to each technology of the list (see Table 1).

In particular, the AD^2 parameter can be associated to each list item looking at the definition reported in Ref. [50] even if, in this case, the experts' judgement has been fundamental to tune the values. Similarly, Starting TRL (i.e., the TRL level of each technology in 2018 at the beginning of STRATOFLY) has been assessed after a thorough literature study and interactions with experts. Specifically, the TRL values reported in Table 1 represent the 2018 European Scenario. Of course, other scenarios can be simulated, such as the US one, thus demonstrating the inherent flexibility of TRIS methodology. Furthermore, as far as the technologies CaC is concerned, due to the lack of real cost data for ATR and DMR technologies, the values reported in Table 1 are estimated by applying the formulation summarized by Eq. (2). Following the approach described in Section C.2, Vehicle LCC is firstly estimated using [42]. Results of LCC estimation in terms of Vehicle RDTE, Vehicle TFU Production and Initial Operations are reported in Table 2. It is worth noticing that, by assumption, STRATOFLY MR3 initial operations include 5 missions in line with Space Shuttle experience [46]. Moreover, Vehicle CaC up to TRL9 (Table 2) is assessed using Eq. (3), while RDTE 1 (or Vehicle CaC (up to TRL 8)) contribution is derived from Eq. (4).

At this point, a costs allocation onto PBS is required in order to derive TDs contribution onto RDTE costs (K_{TDj}). The latter is usually another outcome of LCC methodologies in conceptual design and it can be derived from existing commercial tools, like for example the True Planning software by Price Systems. In the present analysis, the RDTE costs allocation onto PBS reported in Ref. [42] is taken as reference with special focus on Structure and Mechanisms TD (i.e., $TD_{Structures}$), ATR, and DMR. For sake of clarity, DMR and ATR cost represent overall powerplant contribution to RDTE cost, also including Isolator, Engine Controls, Actuators and Engine Materials components. For $TD_{Structures}$, only the cost fraction associated to propulsion plant-related structural elements, such as intake and nozzle, is considered (i.e., $TD_{Structures}*$). As a result, technologies in Table 1 (referred as *Technology List* in Eq. (7)) belong to both Powerplant ($Technologies_{\ Powerplant}$) and Structure and Mechanisms ($Technologies_{\ TD\ Structure*}$) as expressed by Eq. (7) and Eq. (6) can be specialized as in Eq. (8) and Eq. (9).

$$Technology\ List = Technologies_{\ Powerplant} \cup Technologies_{\ TD\ Structure*} \tag{7}$$

$$Technology\ CaC_{i\ Powerplant} = K_{Tech\ i\ Powerplant} \cdot K_{Powerplant} \cdot Vehicle\ CaC_{(TRL8)} \tag{8}$$

$$Technology\ CaC_{i\ TD_{Structures}*} = K_{Tech\ i\ TD_{Structures}*} \cdot K_{TD_{Structures}*} \cdot Vehicle\ CaC_{(TRL8)} \tag{9}$$

where:

$Technology\ CaC_{i\ Powerplant}$ is CaC of ith technology in $Technologies_{\ Powerplant}$;

$K_{Tech\ i\ Powerplant}$ is the weight associated to ith technology in $Technologies_{\ Powerplant}$;

$K_{Powerplant}$ is the contribution of powerplant to $Vehicle\ CaC_{(TRL8)}$;

$Technology\ CaC_{i\ TD_{Structures}*}$ is CaC of ith technology in $Technologies_{\ TD\ Structure*}$;

$K_{Tech\ i\ TD_{Structures}*}$ is the weight associated to ith technology in $Technologies_{\ TD\ Structure*}$;

$K_{TD_{Structures}*}$ is the contribution of $TD_{Structures}$ considering only powerplant plant-related structural components (i.e., $TD_{Structures}*$) to $Vehicle\ CaC_{(TRL8)}$.

For sake of clarity, K_{TDj} reported in Ref. [42] and referred to a hypersonic vehicle are not a fraction of $Vehicle\ CaC_{(TRL8)}$ but of Vehicle RDTE. Nevertheless, taking into account the subdivision proposed in Fig. 3, $Vehicle\ CaC_{(TRL8)}$ is, as a first approximation, equal to Vehicle

RDTE, so that K_{TDj} might be considered referred to *Vehicle* $CaC_{(TRL8)}$ as well. Therefore, according values in Ref. [42] $K_{Powerplant}$ is equal to 0.294 (i.e. powerplant contribution represents 29.4% of *Vehicle* $CaC_{(TRL8)}$ or RDTE cost), while to derive $K_{TD_{Structures}^*}$ a detailed cost analysis to assess the impact of specific components such as nozzle and intake onto Vehicle RDTE costs has been carried out using Price True Planning commercial software. Moreover, Eq. (9) has been re-arranged into Eq. (10) and Eq. (11) to highlight nozzle and intake. From results, $K_{TD_{Structures}^*}$ is equal to 0.43., with 3.98% of $K_{TD_{Structures}^*}$ allocated to nozzle and 10.40% to intake. Looking at the nozzle, 3 technologies are listed in Table 1 so that by equally splitting nozzle RDTE cost contribution among them $K_{Tech\ i\ TD_{Structures}^*(Nozzle)}$ is equal to 0.01327 (i.e. 3.98%/3), while for each of the 4 technologies of intake $K_{Tech\ i\ TD_{Structures}^*(Intake)}$ is equal to 0.026. Resulting CaC values for intake and nozzle technologies are provided in Table 1.

exploiting stakeholders ($K_{SG} = 1$) and criteria ($K_{CAD2}, K_{CTRL}, K_{CCaC}$) weighting factors. The ranked list of technologies is shown in Fig. 9. From results, it can be noticed that PAC Technology shall be considered as the highest priority technology, being associated to high risk and low Starting TRL and CaC. As far ACs/MCs are concerned, the list of elements does not contain alternatives, thus ACs/MCs ranking is not required.

3.5. *Planning definition*

The result of Planning Definition is reported in Fig. 9 for technologies, while Fig. 10 shows examples of ACs carried out at low/medium TRL levels and linked to specific STRATOFLY technologies. Please, notice that Fig. 9 highlights the "Technology Gap" in grey, i.e., the need to freeze technology development to wait for the upgrade of other technologies, thus guaranteeing a complete alignment of TRL Milestones along the timeline. Fig. 10 also shows the possibility for a single AC to be

$$Technology\ CaC_{i\ TD_{Structures}^*(Nozzle)} = K_{Tech\ i\ TD_{Structures}^*(Nozzle)} \cdot K_{TD_{Structures}^*} \cdot Vehicle\ CaC_{(TRL8)} \tag{10}$$

$$Technology\ CaC_{i\ TD_{Structures}^*(Intake)} = K_{Tech\ i\ TD_{Structures}^*(Intake)} \cdot K_{TD_{Structures}^*} \cdot Vehicle\ CaC_{(TRL8)} \tag{11}$$

As described in Section C.2, if cost data allocated on a detailed PBS are not available, an estimation of required RDTE effort shall be performed. This is the case of $K_{Tech\ iPowerplant}$ estimation, which is performed by assigning a label (high, moderate, moderate-high, low-moderate, low, very low) which qualitatively estimates the expected level of RDTE effort for each technology basing on the comments collected from propulsion experts involved in H2020 STRATOFLY project. Each level is then associated to a numerical value (or "weight") which is translated into $K_{Tech\ i\ Powerplant}$. Results of this analysis are reported in Table 3. As a summary, the estimated technologies' CaC up to TRL8 is provided in Table 1.

3.3.2. *Activities and Mission Concepts*

At this point, all information related to technologies is available (i.e., Starting TRL, AD^2 and CaC) and it is possible to define the second category of elements meaningful for roadmapping, i.e., ACs and MCs. In order to derive a complete list of ACs/MCs spanning all TRL levels for each technology, as suggested in Section II·C.3, the definition of TRL levels provided in Ref. [45] has been used as guideline. Furthermore, to improve this list specifically for propulsion technologies development, several literature sources have been considered such as those related to ATREX [52,53] and S-Engine in Japan [54,55]. Moreover, the list has been enriched with information useful to propose flight demonstration missions at higher TRL from Ref. [47]. For sake of clarity, Table 4 collects the list of ACs/MCs required to perform technology development up to TRL 9 for PAC Technology. It also reports, for each AC/MC, the Enabling and End TRL. As already mentioned, in case several MCs are connected to the same Enabling TRL, they shall be all successfully performed in order to effectively succeed in the TRL transit. A similar list of ACs/MCs has been derived for all technologies in Table 1.

3.4. *Prioritization studies*

Following the upgraded methodology, technologies' prioritization consists in a trade-off analysis to rank the list of technologies according to criteria previously defined by stakeholders and exploiting technology data from Table 1. In particular, available technology data shall be properly normalized according to the prioritization order (i.e., ascending/descending) assigned by EC stakeholder to each criterion and

used for the development of several technologies, especially for medium TRL transits. Moreover, applying the newly derived CaC distribution in Fig. 4 (b) to Vehicle CaC (up to TRL 9) in Table 2, Fig. 9 highlights the costs associated to TRL transits 6 to 7 and 7 to 8 with the aim to show the capability of proposed TRIS methodology to assess the cost of meaningful TRL milestones linked to technology demonstrators. From the technology roadmap depicted in Fig. 9 it might be stated that all technologies may reach TRL 6 by 2035 if no out-of-nominal events would occur and, most importantly, if available budget would be sufficient to cover CaC of all technologies. In addition, the following milestones might be envisaged:

- Small-Scale Demonstrator by 2038;
- Mid-Scale Demonstrator by 2042;
- Near Full-Scale Demonstrator by 2047;
- Beginning of STRATOFLY MR3 Operations from 2050.

Therefore, according to the assumptions discussed above, the upgraded TRIS methodology from Politecnico di Torino described in this paper is proven to be able to propose a technology roadmap for key enabling technologies in H2020 STRATOFLY project, verifying project's goal to assess the potential to reach TRL 6 by 2035.

4. Conclusion

This paper has presented the upgrades introduced to the roadmapping methodology (TRIS) already proposed by Politecnico di Torino in Ref. [13] to increase its flexibility and to widen its applicability to different hypersonic vehicle configurations and missions. In addition, the application of the methodology to the H2020 STRATOFLY Project has highlighted the level of maturity of enabling technologies for future hypersonic vehicles, that can operate both as high-speed civil passenger transport aircraft and as first stage of reusable access to space vehicles, thus delineating multiple paths to complete the technology development program to support strategic decisions.

From the methodology standpoint, the elements of novelties introduced by the authors in this paper are summarized hereafter:

o For the first time, a clear and practical example of integration of technology roadmapping process into conceptual design activity flow has been reported. This practically consists in the possibility to exploit the Vehicle Breakdown Structure and the Vehicle Life Cycle Cost Estimation to guide, respectively, the derivation of the list of technologies and its characterization in terms of costs using a new semi-empirical model for budget estimation.

- o Precise and practicable guidelines to support the definition of activities, demonstrative missions or in-flight missions have been reported. Based on the TRL definition manuals, the paper has suggested a rational way, to associate each TRL transit to specific research activities, tests in laboratory, demonstrative missions or real flight missions.
- o More accurate prediction of time resources needed to accomplish technology development has been disclosed in form of semi-empirical model.
- o Stakeholders' Analysis has been placed at the beginning of the overall process to stress its crucial role in steering the decision-making process. As a direct consequence, the prioritization routine has also been improved to guarantee that stakeholders' needs are duly taken account during the technologies' ranking process, guaranteeing a complete traceability throughout the process.

The application of upgraded TRIS methodology in the framework of the H2020 STRATOFLY project has clearly revealed its potential in supporting strategic decisions in the aerospace domain and even beyond that. The technology roadmap has confirmed the potential of key-enabling air-breathing propulsive technologies for high-speed to reach TRL 6 by 2035. The roadmap has also been enriched with a long-term vision, by suggesting a possible incremental path towards the final maturation of technologies by 2050. For the first time, a detailed formalization of hypersonic technologies, activities and missions required to target an entry into service in 2050 has been presented. The paper has disclosed a unique example of comprehensive technology assessment, which clearly depicts the status of the European developed technologies in the field of high-speed air-breathing propulsion, thus suggesting where to concentrate funding opportunities to strengthen the leadership in the sector. Special attention shall be devoted to the suggested demonstrative missions which are fundamental to complete the technology development process. The three demonstrators suggested by TRIS are supported by specific time and budget resources allocation, thus providing a clear indication to all entities involved into the decision-making process.

Future works will deal with a deeper analysis of other enabling technologies for future hypersonic transportation systems, as well as a sensitivity of results, by considering, for example, the impact of additional stakeholders (e.g., research centres, operators, e.g.) into the analysis and by varying time constraints (i.e., the date for final TRL9 achievement), to assess the possibility to reach the same TRL goal by changing initial assumptions.

In addition, the authors are currently working at extending the scope of the presented technology roadmapping exercise, to target future air/space high-speed mobility, such as future suborbital vehicles as well as reusable access to space and re-entry vehicles.

Fundings

This research was funded by European Union's Horizon 2020 research and innovation programme under grant agreement No 769246 - Stratospheric Flying Opportunities for High-Speed Propulsion Concepts (STRATOFLY) Project.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors wish to thank the propulsion experts involved in STRATOFLY H2020 Project for their valuable support during the definition of propulsive technologies to be considered and related technology data.

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