Innovations

The Contribution of Innovation Management Practices in Aerospace to Technology Roadmapping

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Abstract: *This study investigates the reciprocal relationship between the aerospace industry and academic schools of thought in the field of technology roadmapping (TRM) through a systematic literature review. Employing a multi-method approach, the research integrates textual analysis of keywords and abstracts, author co-citation analysis, and manual qualitative thematic coding to identify developmental patterns and interconnections between academic and industrial research. The analysis reveals the emergence of two distinct research flows within TRM, highlighting evolving theoretical and practical paradigms. The findings contribute to a deeper understanding of the synergies between industrial innovation and academic research.*

Keywords: *Technology roadmapping, aerospace, R&D planning, bibliometric analysis, literature review*

1. Introduction

Technology roadmaps (TRM) are often considered as one of the most influential tools for technology management (Yoon & Phaal, 2013). Roadmapping assists in developing and implementing business and product strategies as it integrates information, processes, and tools for comprehensive planning (Phaal *et al.*, 2004). Unsurprisingly, aerospace companies were among pioneering TRM users (Kerr & Phaal,2020). Moreover, enterprises and organizations are proceeding today with a broader application of TRMapproach. For instance, it has been used by the European company airplane manufacturer (Daim, 2018), while NASA has developed more than 14 documents of that type in the early 2010’s (Geet *et al.*, 2015).Subsequently, asimilar instrument has been developed for the European Space Agency (Cresto Alenia *et al.*, 2016). However, there is still a disproportion between the number of published aerospace-related roadmapping results and publications in modern academic literature, reflecting in the share of publications by authors associated with the aerospace industry which accounts for only 3% (Ding *et al.*, 2023). Consequently, this leads us to the research question: is aerospace industry still can be considered as animportant driver of TRM development stream? Thus, this article aims to investigate the interconnection between the aerospace industry roadmapping experience and academic practices through a systematic literature review.

2. Roadmaps and roadmapping

Roadmapping, a strategic planning tool initially developed and introduced by Motorola in the late 1970s (Willyard & McClees, 1987), further has been adopted by several leading organizations, such as Philips (Groenveld, 1997), Lucent Technologies (Albright & Kappel, 2003), and the Semiconductor Industry Association(Kostoff & Schaller, 2001). Hence, a roadmap as a result of roadmapping process is a comprehensive plan or an explanation to guide progress toward a certain goal, while roadmapping is a process of the roadmap creation(Phaal *et al.*, 2001) based on expert assessment, interaction, creativity.Roadmap acts as decision support to improve the coordination between activitiesand resources (Sourav *et al.*, 2016). It helps to identify, evaluate and select available technological development options to meet a wide range of needs (both organization and market) (Gerdsri, 2010).

One of the first systematically described roadmapping processessuggested by Sandia National Laboratories (Garcia, 1997) included three phases:preliminary activity, roadmap development, and follow-up activity Its variants were applied for technology planning in a variety of emerging technologies such as microsystem and nano-system (Walsch, 2004), semiconductor silicon industry (Walsh, *et al.*, 2005), and pharmaceutical technology (Tierney *et al.*, 2013). As the roadmapping application field continued to grow, it became possible to distinguish at least three TRM categories:product roadmaps; emerging technology roadmaps; issue-oriented roadmaps.Typical roadmap structure is based on a “three-part scheme” consisting of so-called “layers”: market, product, technology (Phaal *et al.*, 2001). All other approaches represent a modification of the “three-part” scheme by adding new layersto the roadmap. Thus, the roadmap graphical representation is appreciated for its applicability to illustrate the directions of possible progress in both the demand (market conditions) and supply (scientific and technological evolution), that made it attractive for information support for the future decisions.

A notable milestone in the advancement of roadmapping methodology was the publication of Phaal's "T-plan" workbook in the 2000s (Phaal *et al.*, 2001) which proposed strategic,service/capability and program planning roadmaps. This contribution marked a significant methodological progress byoffering a more structured and comprehensive approach to roadmapping and presumably induced the popularization of the method among scholars.

Originally designed to improve the alignment between technology and innovation, roadmapping has expanded to cover even broader spectrum of applications. It has been utilized to map out product or technology groups within organizations and even whole industry sectors (Vishnevskiy, 2016). This has demonstrated the versatility and adaptability of the roadmapping approach to address various planning needs. Summarizing over twenty years of academical TRM-related research Kerr & Phaal, (2020) identified seven distinct "schools of thought" and presented research challenges for the future.The Cambridge practical school (Phaal *et al.*, 2001)focuses on workshop-based roadmapping methods and their substantial application in various sectors, while the Seoul school emphasizes on evidence-based roadmapping and toolkits to generate roadmaps omitting workshops. In turn, the Portland (Daim & Oliver, 2008)school combines decision-making approaches with roadmapping processes. Furtherly the Bangkok school focuses on implementation-oriented roadmapping (e.g. Gedsri, 2005). Finally, the two "then-emerging" schools, the Beijing (e.g. Zhang*et al.*, 2013; Li*et al.*, 2015)and the Moscow ones, have the following features. The Beijing(e.g. Zhu et al., 1999)approach is recognized for combining bibliometrics with qualitative data in roadmapping, while the Moscow ISSEK's(Saritas, 2010)school focuses on integrating TRM with scenario planning, bibliometrics, and scientometrics.

At least six comprehensive literature reviews related to TRM have been issued since 2010 (Gersri *et al.* 2012; Carvalho *et al.*, 2013; Alcantara *et al.*,2019; Kerr & Phaal, 2020; Vinayavekhin *et al.*, 2021, Ding, 2023). All mentioned works have been focused on the general management audience, providinga comprehensive view on the "mainstream" academic TRM- related activities in a number of contexts. On the contrary, this paper focuses on the actual TRM-related issues in aerospace sector that have not been covered in the papers mentioned above. Despite the fact that Kerr& Phaal (2020)gave a tribute to the significant aerospace contribution in the past, as to our knowledge, few papers discussed above focuses on actual interrelationsbetween academic and the industry with regard to TRM development. Hence, the mutual influence of modern practices in technological roadmapping developed, on the one hand, by the aerospace industry, and on the other, by the academic community, remains understudied. This article aims to fill this gap by analyzing roadmapping practices along with TRM methodological features in aerospace.The next sections sequentially present the methodology, results, and conclusions of this research.

3. Methodology

The research is based on a systematical, clear and reproducible methodology which allows us to generate new research findings. In particular, this paper finds its methodological basis in the systematic literature research (SLR) procedures of Tranfield *et al.* (2003), and the recommendations of Anand *et al.* (2021). The SLR procedure involved the following steps: data base selection, keywords finding and analysis,author co-citation analysis (CCA), and manual coding and content analysis.

The author relied on the VOS Viewer software (Van Eck & Waltman, 2010) for the visualization of keyword analysis and CCA.

For initial data set of relevant publications has been extractedfrom the Elsevier`s "Scopus" database. First, I conducted a keyword search to find publications for further analysis. While preparing a search query, different spelling alternatives have been tested. However, the initial search showed that, despite expanding the list of keywords, the system returned 17-23 papers only.To expand the dataset, I implemented an additional search thathas been carried out using the Google Scholar. Contrary to the widespread practice, due to the limited amount of relevant data I decided not to be limited to articles in the "business" subject area, expanding our search also on "engineering". The resulting data set contained 40 items, from which it became possible to get19relevant items through the manual reading of the abstracts and full texts (see Table 1).Next, it became able to find in Scopus six of ten articles previously found in Scholar in order to include them into the bibiliometric set that allowed us to implement the co-citation analysis.

Table 1 – A data extraction queries and scheme

Database	Search query	Publi-cations found, total	Relevant publications	Total
Scopus	(TITLE-ABS-KEY ("technology roadmap*")) AND (TITLE-ABS-KEY ("aircraft*" OR "aviatio*" OR "aerospac*" OR "aeronautic*")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "BUSI")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))	17	10	19
	(TITLE-ABS-KEY ("technology roadmap*") AND TITLE-ABS-KEY (("Boeing*" OR "Lockheed*" OR "Airbus*" OR "Embrae*" OR "Northtrop*" OR "ESA" OR "DLR" OR "NASA" OR "JAXA" OR "aviatio*" OR "aerospac*" OR "aeronautic*")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (SUBJAREA , "SOCI") OR LIMIT-TO (SUBJAREA , "BUSI") OR LIMIT-TO (	23		

	SUBJAREA ,"ECON") OR LIMIT-TO (SUBJAREA ,"ENGI")) AND (LIMIT-TO (LANGUAGE , "English"))			
Google Scholar	"technology roadmap" + "aerospace"	10		
	out of it subsequently found in Scopus	7		
	out of it subsequently not found in Scopus	2		

Additionally, to distinguish interconnections between TRM-related academic and the investigated fields, I compared of the keywords and results of the CCA from the selected sources with the keywords and sources used in the analysis of the main body of knowledge in the field of roadmapping. For that purpose, another set of Scopus bibliometric data was obtained through the request "technology roadmap" and with a search limit to business, social and economics. This set accounted 596 articles.

Data processing included the two steps. In the first step,I implemented comparative text keyword analysis as well as CCA analysis based on authorship. The base of analysis consisted of 17 sources for which is was possible to get Scopus bibliometric data. In the second step, a textual coding of the 20 obtained sources was implemented. While doing the latter, we used bibliometric analysis coupled with science mapping and visualizing instruments (Walsh & Renaud, 2017). Among such tools I choose visualization software VOS Viewer (Van Eck & Waltman, 2010)for mapping bibliographic information and citations into clusters, allowing us to find new trends and dependencies in the field of study. Hence, by synthesizing the results of those two steps Icame to the main findings of this research: determination of new TRM clusters and inductive understanding of the main ideas represented in the analyzed items.

Subsequently, I conducted qualitative descriptive coding and content analysis based on the guidelines of Anand *et al.* (2021). At this stage the key ideas of the extracted papers were interpreted and consolidated. The results of the analysis and discussion are presented below.

4. Results and discussion

4.1Keyword analysis

Considering the difference in sampling power, to obtain an interpretable picture, for a sample of 17 articles keyword frequency threshold was set to not less more than 5, while for a sample of 596 articles – not less than 25. The comparative keyword visualization presented in Figure 1. As it can be interpreted, the aerospace TRM application scope is presumably more focused on product development related activities, rather thanon planning and forecasting issues – things, that arepresumably typical TRM applications in business and social sciences.Thus, aside of industry-specific "aerospace", "ESA", and "aircraft", the "aerospace-specific" keyword set contains such terms as "development", "experiment", "energy", "technology readiness level" or "TRL", and "methodology". Simultaneously, the business and social set operates with the terms "scenario", "planning", "roadmapping", "policy", "variety", "effort" etc, representing focus on planning, forecasting and the process of roadmap development. Consequently, sets of the most frequent 15 keywords of 17 aerospace-related articles and 30 keywords of 596 articles have only two common points – "TRM or "roadmap" as the core concept and "case study" as the most frequent TRM-associated research method.Additionally, it is a notable fact that the term "strategic planning" is also not typical for aerospace TRM-related publications.

4.2 Co-citation analysis

Both Two well-spread approaches to co-citation analysis (CCA): first, based on reference data; second, based on authors' citations, have been implemented.However, only authors-based CCA approach led to interpretable results, presented in Figure2. The analysis allowed to distinguish three clusters.While the cluster marked red in the left part of the Figure represents "classical" academic roadmapping authors, the two other clusters, marked blue and green, as to our knowledge, have not previously been mentioned in the context of roadmap methodology. It helps us to assume the possible development of two emerging TRM-related clusters: MIT-Scoltech and ESA-Polito[1]. Subsequently, author could find additional arguments for the mentioned assumptions via the content analysis and qualitative coding described in subsection 4.3.

4.3 Content analysis

<u>NASA cluster (six sources)</u>

In addition to co-citation analysis, the use of quantitative coding and content analysis allowed to reveal the additional cluster of roadmapping-related publications made by NASA.Assumingly, up to the mid of 2010's, NASA remained the important but enclosed domain of roadmap implementation. Consequently, due to the limited publication activity regarding TRM practices, author could distinguish only six papers, in which qualitative coding approach made it possible to recognize the following streams: description of the TRM results (McConnaughey, 2012; Johnson, 2013), (2) description of the necessity of more collaboration while roadmapping (Betser, 2016; Cavender, 2018) which links the first stream to the third one, represented by Rodgers, (2021). Finally, the fourth stream represented by Cole (2014) describes NASA's approach to cost estimation of early-staged tech projects.

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Polito – Politecnico di Torino, https://www.polito.it/

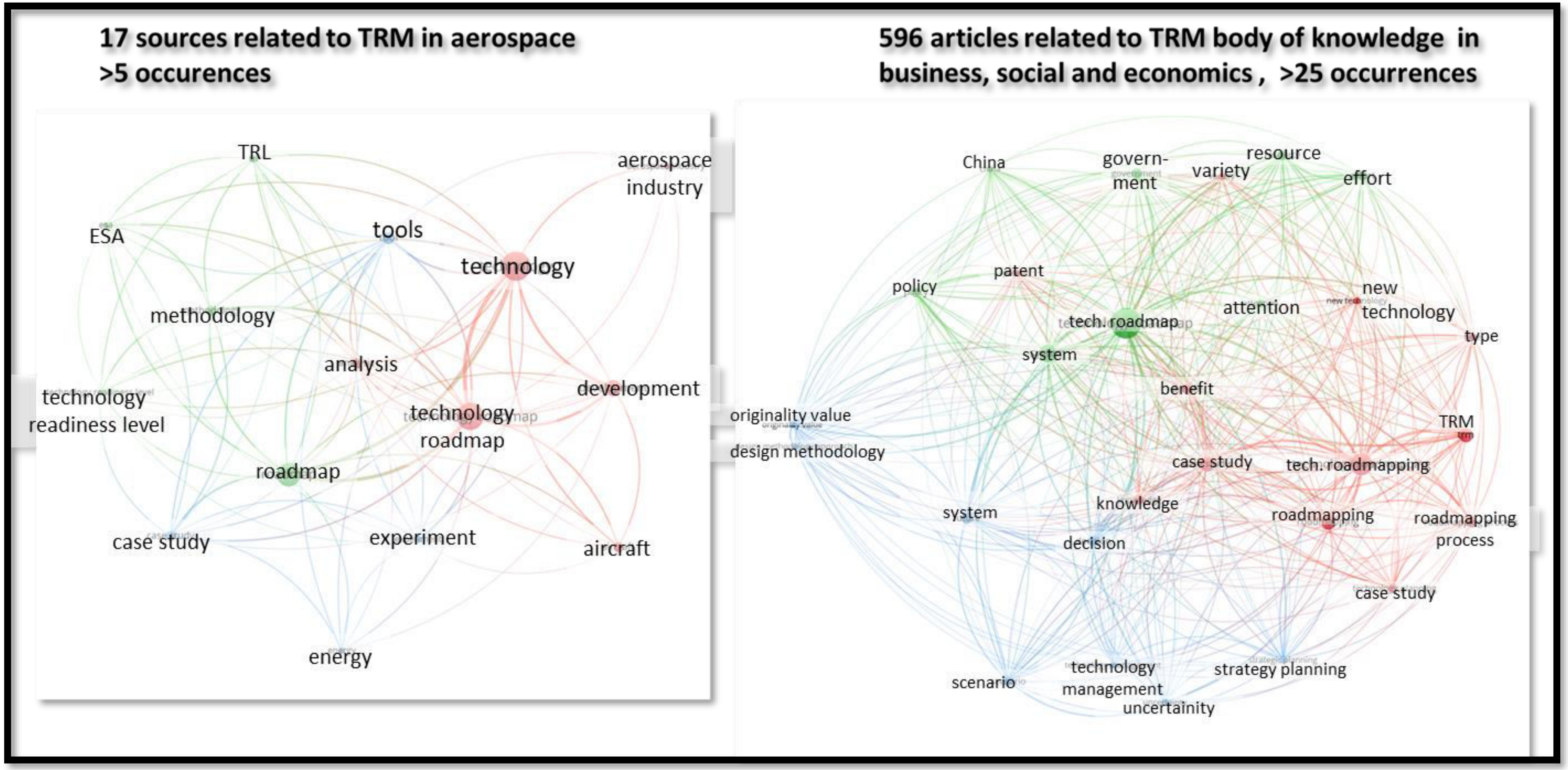

Figure 1 – Comparison of frequently met keywords from articles related to aerospace (left) and business, social and economics (right) according to Scopus classification

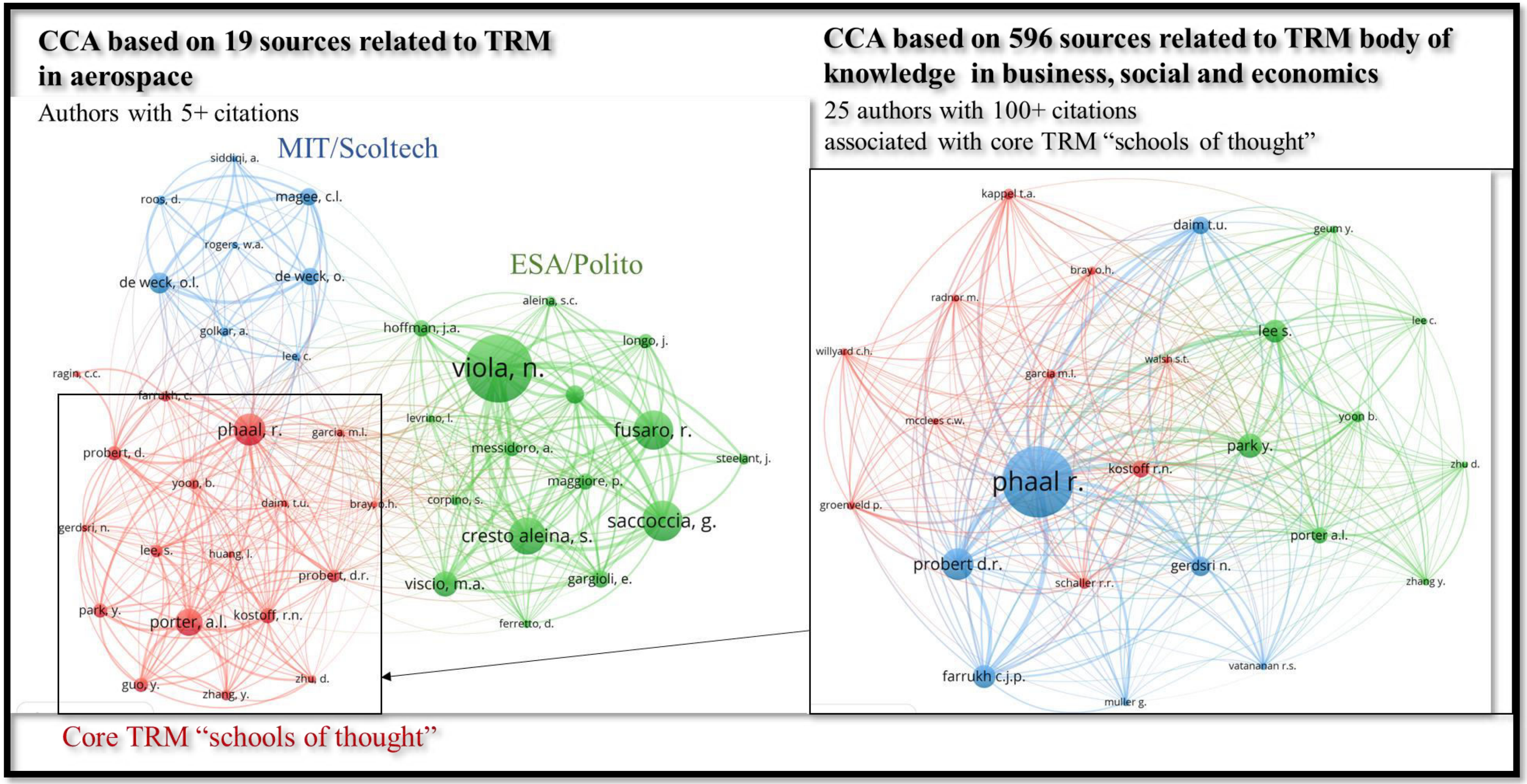

Figure2 – The results of CCA analysis

The analysis of the mentioned papers reveal at least two consequent attempts of roadmapping – unsuccessful and acceptable. respectively. The first one was presumably full-in-house, while the second one widely used external expertise, including academia. Thus. McConnaughey (2012) and Johnson (2013) described an overview of the roadmap of the Launch Propulsion Systems Technology Area (LPSTA) and In-space Propulsion Systems, respectively. Despite the engineering orientation of these papers, both contain the valuable artifact – description of NASA's technology roadmapping sequence that presumably has been implemented for the first roadmapping attempts (see Figure 3).

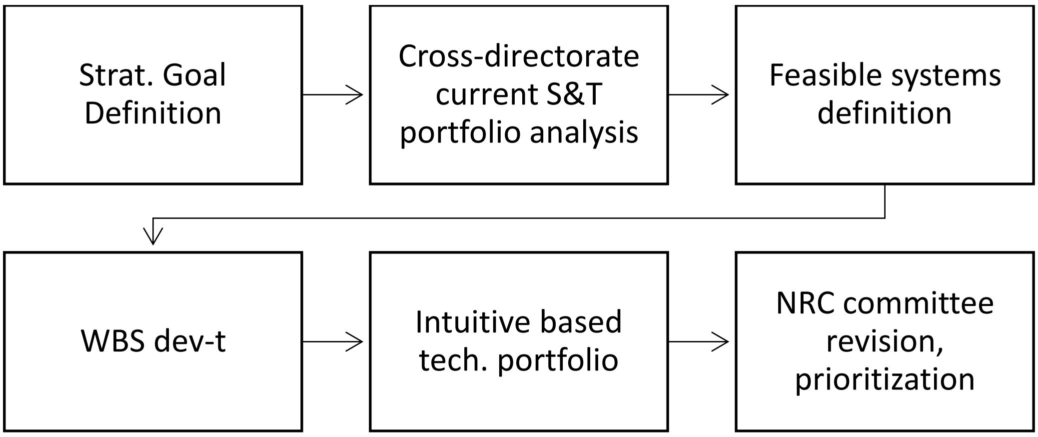

Figure 3 – A generic roadmapping process in NASA during the first attempt of TRM creation

Sources: McConnaughey (2012), Johnson (2013)

However, although roadmaps were created, Rodgers (2021) estimated this attempt as not entirely successfulthat resulted in roadmap revision process in 2015. The reasons for this decision, as follows indirectly from Betser (2016), and Cavender (2018), lie in an insufficiently systematic and isolated approach to roadmapping that violated the TRM practical integration.Namely, in the beginning of the practical use of the roadmaps a significant overlap in the topics proposed by scientists was discovered, as well as the impossibility of prioritizing technology development at the level of the entire Agency. Subsequently, this led to the initiation of the systematic roadmap development process at NASA with introduced two new important features: first, the broad involvement of external experts for consultation; second, the necessity of agreement on the developing results among stakeholders. It should be mentioned that the involvement of key organizations representatives in the roadmapping process and the introduction of feedback mechanisms between them makes it possible to achieve an important network effect: an institutional environment is formed that is favorable for the implementation of the innovation strategy proposed in the roadmap. Thus, by the end of the 2010s, as noted by Rodgers (2021), NASA was able to build a roadmap-based strategic planning system, in the middle of which intensive external expertise has been incorporated (marked with a red frame in Figure4). Thus, the appeal to external expertise, largely based on academic knowledge, was assumingly an important factor that lead to advancement of NASA's TRM procedures.

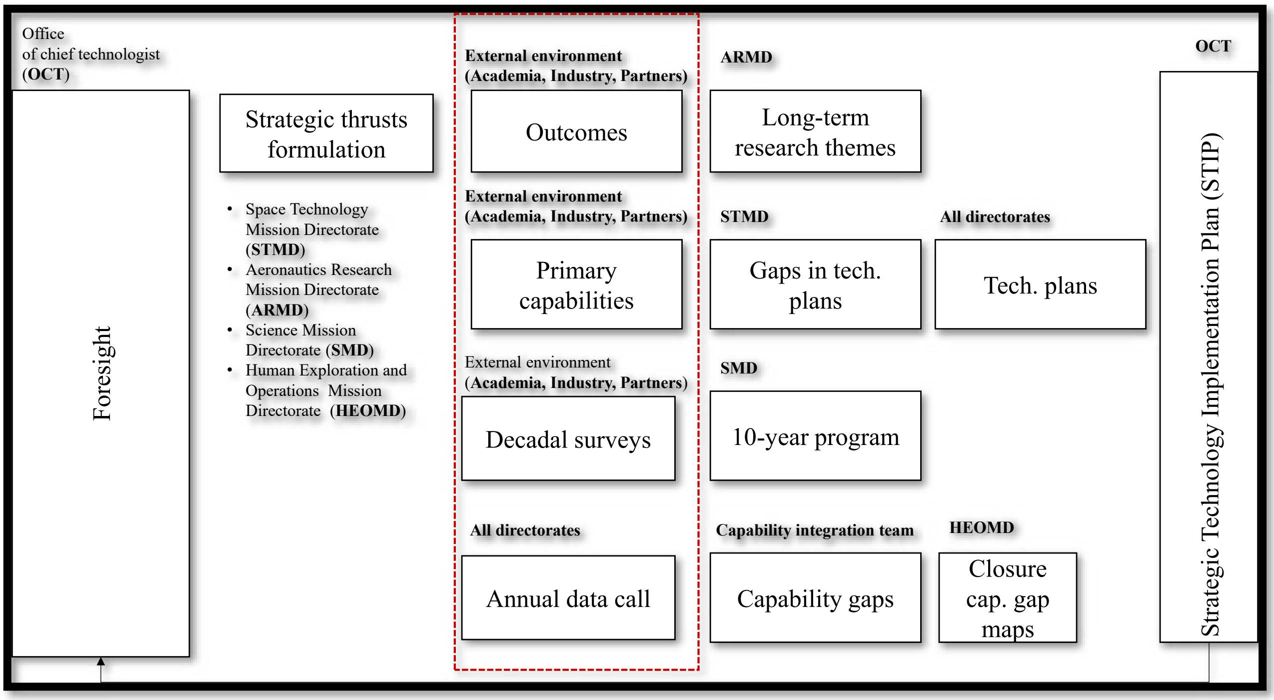

Figure 4.Top-tier scheme of advanced roadmapping process in NASA

Source: Compiled by author based on Rodgers (2021)

Finally, Cole (2014) representsasub-stream, having anindirectbutimportantrelationshiptothecreationoftechnologyroadmaps. This research focused on the cost evaluation methods for projects aimed to increase the technology maturity frequently measured with the Technology Readiness Level scale (Mankins, 2009) from TRL 2 to TRL 6. The author concludes that estimating the costs of such project is rather complicated but is fundamentally possible, although will always have a wide variance. This conclusion is important because the more modern methodologies described below, developed by scientists in the next two clusters, contain functionally identical assessment modules.

"Classical" academic cluster (five sources)

Basedon the chosen data set it was possible to discover the contribution of four academic schools, the leading Cambridge (Farrukh*et al.*, 2000) and Portland (Sourav, 2018)universitiesas well as Moscow-basedISSEK (Vishnevskiy *et al.*, 2015) and Beijing-school branch from GeorgiaTech(namely, Lahoti *et al.*, 2018) schools that can be attributed to the "classical" TRM-related researchers according to classification provided by Park*et al.* (2020).To understand the evolution of the studies,they are discussed chronologically below.

The first evidence of collaboration in the analyzed set of articles refers to Farrukh *et al.* (2000) devoted to the outcomes of the consulting project for the United Kingdom-based defense corporation, BAe Systems. Through the analysis of the literature, andseries of meetings with the company's representatives,authors conclude that qualitative approaches to the selection of R&D projects are in demand in real practice much more than quantitative ones created by scientists in the academic environment. Therefore, as an outcome scholars contributed to practitioners by introducing a qualitative approach to prioritizing the choice of technologies based on weighted scoring of (1) the value of the project for the internal consumer and (2) the qualitative indicator "benefit/cost" combined using a speciallydesigned portfolio matrix.

Furtherly, the conclusion regarded to the preference of qualitative approaches over quantitative for practical use was supported in the on-going Cambridge – affiliated study (Dissel *et al.*, 2006), that focuses on the comparison of academic and business-originated approaches to technology benefit measuring techniques. The paper discusses the controversies and the existing research gaps with regard to the new technologies' valuation.Explaining the reasons for the moderate attitude to the implementation of quantitative approaches such as DCF, real options, and decision tree, authors suggest the use ofqualitative methods of valuation such as the suggested "value roadmap" at the early phases of maturation. As the result of four case studies from the aerospace, the authors defined as the research gap the *insufficient integration* between financial and technical technology valuation. Consequently, the discussed research illustrates the cross-fertilization between academia and aerospace: inductive generalization of four aerospace-originated cases resulted into prioritization approach applicable by industry.

Additionally, two more cases discuss the later TRM applications of academic-originated approaches to aerospace.

First, as it was noted by Vishnevskiy *et al.* (2015) the team of the ISSEK division of the Moscow-based Higher School of Economics (HSE) applied a combined TRM-approach to a series of domestic aerospace enterprises between 2008 and 2013. Specifically, the proposed technique could be considered as a more sophisticated cross-industrial approach based on a combination of Foresight and integrated technology roadmaps (Vishnevskiy *et al.*, 2016), and business-planning techniques. Within this approach a long-term forecasting methodology known as "Foresight" (Rohrbeck *et al.*, 2015) considered as a bridge between the so-called "push" (technology-driven) and "pull" (market-driven) approaches to roadmapping, while the TRM artifact, in its turn, depicts the key results of foresight. Aiming to elaborate innovation strategies, integrated roadmaps use a set of plans allowing to schedule the further R&D steps. Similar to Farrukh *et al.* (2000), a special qualitative portfolio matrix used as the R&D set selection tool.

Second, Sourav *et al.* (2018) discusses the useof the classical approach of Portland University to technology roadmapping for a major commercial aircraft industry company, focusing on the development of single-aisle aircraft for the fast-growing Asian airlines.The roadmapping process suggests the7-step process (see Figure5)focused on identifying market drivers, establishing connections between market drivers and product features, and suggesting technologies to close the gap in product features using SWOT (Ghazinoory, 2011), qualitative expert techniques based of the Quality Function Deployment method (Vanegas, & Labib, 2001). Although the paper focuses on the practical task, it also emphasizes the importance of external resources, such as university partnerships, subcontractors, startups, and collaborations with other firms, in reducing research and development (R&D) costs and bringing expertise. Moreover, it also discusses the limitations of roadmaps and suggests future research involving the implementation of risk and uncertainty analysis.

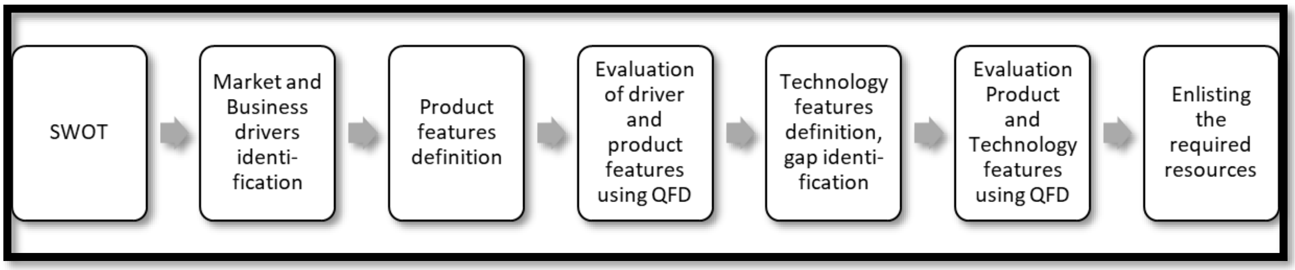

Figure5. Process steps in the TRM development by K. Sourav, T. Daim and C. Herstatt

Source: Made by author basedonSourav *et al.*, 2018

Unlike the four papers described above, the last evidence of academic contribution is related to the specific purpose as a fact-check. However, the case of Geet *et al.*(2015) allows to establish a link with the previously discussed NASA TRM activities. Specifically, according to the paper, the team of GeorgiaTech (USA) has developed text-mining tools to support the validation of roadmap of nanotechnology for aeronautics during those 2012 revisions. The researchers aimed to validate predictions made duringthe NASA Nanotechnology Roadmap developed to provide additional information on emerging technologies. The study uses publication and patent records to identify trends and assess the maturation of various nanocomposite coatings. It discusses a comprehensive methodology involving data collection, text mining, and analysis of clusters to distinguishtrends. Findings suggest that tech mining can be an effective tool for technology roadmap validation and refinement, providing empirical information to complement expert knowledge.

To conclude, the presented piece of analysis illustratesthe series of mutual benefits received to both industry and academics. Having the opportunity to turn to the real practice of manufacturing companies, scientists were able to adjust the direction of methodological attempts while the industry benefited from gaining the applied tools for technology prioritization. The important observation hadalso been related to such questions as: importance of collaboration, making regular updates of TRM, and the balance between qualitative and quantitative tools.

ESA-Polito emerging cluster (six sources)

Along with NASA, data coding and author-CCA made it possible to identify a new developing roadmap methodology cluster associated with Politecnico di Torino, which presumably has developed roadmapping tools for another aerospace entity, the European Space Agency (ESA).The evolution of this research stream from its roots and up to the implementation is made through the analysis of six papers presented below.

First, Cresto Alenia*et al.* (2016) introduced the original semi-automated data-supported methodology, which had been designed to prioritize R&D activities in technologies for space exploration. The methodology operates with four interrelated categories: Operational Capabilities (mission statements), Technology Areas (a set of technologies that accomplish one or more missions), Building Blocks (technologies), and Mission Concepts (approved missions). Through the establishing correspondence between those categories, the method allows to semi-automatically define the technology sets most and less preferable for the particular mission measured with a novel quantitative indicator – the"pseudo-TRL", based on the popular indicator of "Technology Level Readiness"(Mankins, 2009). This research has been also stated that considering the logical analysis application of this method may lead to the understanding that set of technologies is more preferable to be maturated to fit the mission requirements.

Second, the research of Cresto Alenia *et al.* (2016) contributed to the methodology for rational roadmap generation, adaptable for a broader number of industries (Cresto Alenia *et al.* 2018; 2019), based on a multi-step procedure. Particularly, the described methodology incorporates such steps as stakeholder analysis, a hierarchical multi-level functional analysis, definition of operations concept, andtrade-off analysis. Although the methodology was claimed as successfully implemented, it has also been found that it is, first, overcomplicated and, second, unsuitable for finding new types of technologies. It was suggested running the on-going research, aimed to use aTheory of the Resolution of Invention-Related Tasks (Mann, 2001) to mitigate the first of the two mentioned downsides.

Third, two yearslater,the similar approach became the subject of a newly published paper where the adjusted and detailed points of (Cresto Alenia *et al.* 2018)have been presented as the TRIS methodology (Technology Roadmapping Strategy) in the context of then-ongoing collaborative research program aimed to create a hypersonic Earth-atmosphere re-entry sub-orbital vehicle (Viola *et al.*, 2020). Additionally, the more recent publications demonstrate the application of the methodology to the ESA H2020 STRATOFLY Project with a TRM as a deliverable (Vercella *et al.*, 2021) and introduced three methodological additionsto TRIS. First, stakeholder analysis at the beginning of the roadmapping procedure. Second, an ability exploitation the breakdown structure of the target systemautomatically. Finally, an enhanced precision of cost estimation and allocation of R&D activities (Viola *et al.*, 2022).

Thus, the considered case represents a real example of the successful implementation of TRM methodology created by the academic research team in close cooperation with the ESA.The later allows author to suggest that successful transfer of the obtained academic knowledge if related to the level of collaboration, that was fundamentally deeper than in all previously cited examples. The synthesis into the sole methodology techniques and methods, typically used either in business(e.g. definition of requirements, stakeholder analysis) or in engineering (e.g. TRL, optimization methods, correspondence matrices, specifications sensitivity analysis) makes it possible to assume the significant productivity of such cooperation. Moreover, it should be noted that the developed approach apparently provides a significant degree of roadmapping automation, something that was previously presumed as rather difficult to achieve (Kerr & Phaal, 2020).

MIT emerging cluster (two sources)

The fourth and the second emerging cluster identified through the CCA analysis includes two publications of unequal impact, both of them related to professor O. de Weck MIT the Apollo Program Professor, Professor of Astronautics and Engineering Systems.

In his monography de Weck (2022) presents a comprehensive overview on intra-aerospace technology planning techniques, activities, cases, and approaches.Apart from the thorough description of NASA's modern roadmap system,it systematically describes the methodology that has presumably beenadopted by NASA[2]. The advanced technology roadmap architecture (ATRA) methodology initially based on Markowitz's portfolio theory (Francis, J. C., & Kim, D., 2013) suggests 4-stepapproach. While the first step involves assessing the current position involving multiple stakeholders in workshops, the second step focuses on exploring potential new products, services, or technologies through qualitative and quantitative models, highlighting the importance of using the co-called Concurrent Design Facilities (CDF). The third step involves prioritizing proposed product and technology scenarios, setting specific targets, and aligning them with strategic inputs. Finally, the fourth step focuses on fitting proposed scenarios, R&D projects, and new demonstrators into an overall budget envelope.

The analysis of the second source of this cluster showed that scientists from the Moscow-based technological institute Scoltech were involved inthe development of the part of the Weck's ATRA approach. Specifically, Knoll *et al. (2018)* discuss the

[2] NASA has recently selected the ATRA framework for researching improved ways of managing its technology portfolio, see: https://www.nasa.gov/directorates/spacetech/strg/early-stage-innovations-esi/esi2020/astra/

limitations of traditional technology roadmaps and propose a model-based approach to build technology roadmaps using concurrent design, which is a technique used previously for reducing costs and total duration of product development (Domizio and Gaudenz, 2008). Explaining the core idea (see Figure6) using an example of the roadmap of a notional Solar Electric Airplane, authors assume that concurrent design applied to TRM may help to come to a more evident connection between technology targets and their scientific rationale, as well as to identify synergies across multiple technology areas.

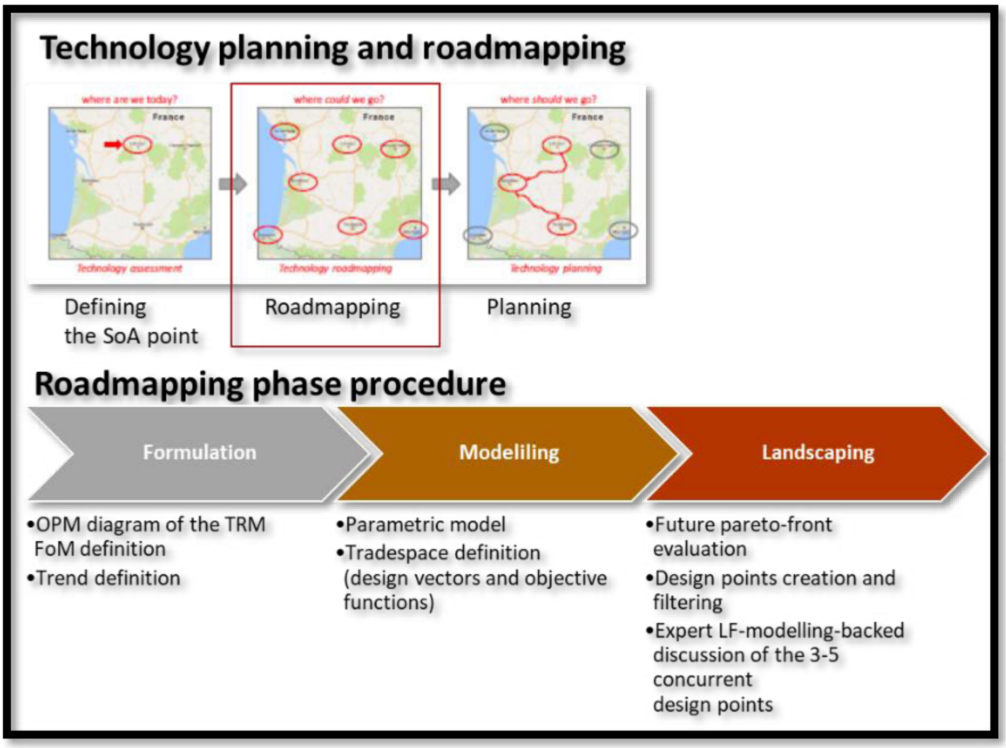

Figure6 A scheme of the concurrent roadmapping approach

Source: Knoll *et al.* 2018

Thus,the described papersallow us to presumably unite MIT and Skoltech institutions into a single developing TRM cluster.Hereit is important to note, that MIT-Skoltech approach had never been discussed in the previously made TRM-related literature reviews as well as the researches of ESA-Polito cluster. Moreover, the fact of implementation ATRA into the NASA business processes provides the second evidence of both positive and productive close collaboration of aerospace and academic institutions. Additionally, compared to the context of NASA cluster case provided above it also may illustrate the effectiveness of such cooperationcompared to fully in-house approaches.

Overall, the author-CCA analysis and qualitative coding made it possible to distinguish

four clusters of publications. Two of them relate to such traditional (although rather autonomously developed) TRM-related centers of knowledge as NASA, and traditional academic schools. The two others, ESA-Polito and MIT-Skoltech, are newly developing clusters distinguished by author.Those two clusters have been apparently developed through synthesizing the ideas of the classical Portland and Cambridge practical TRM schools with engineering (e.g. concurrent design in MIT-Skoltech) and general management approaches (e.g. SWOT in ESA-Polito).Thus, the discussed above interconnections between the clusters qualitatively describe the routes for the assimilation of TRM-related competencies among the beneficiaries of this knowledge.

Comparison of collaboration patterns and methodology

The analyses presented above made it possible to distinguish six cases of collaboration between aerospace and TRM-related academia, compared in Table 2. First, data comparison made it possible to classify the cases into two types of partnership relations between academia and industry: adoption and collaboration. Second, by aligning the cases by time it has been shown the tendency of transition from an adoption of existing solutions towards roadmapping collaboration between aerospace structures and scholars. Additionally, it was able to distinguish a tendency towards more widespread use of quantitative methods in recent cases of aerospace-academia collaborations.

Table 2. Types of relations between aerospace entities and academia and methodology use during technology roadmapping projects

Case, reference	**Partners involved**			**Mutual contribution**		**Methodology used**
	Academia	**Aerospace entity**	**Type of relations**	**Academia to Aerospace**	**Aerospace to academia**	
Technology prioritization (Farrukh *et al.*, 2000)	Cambridge University	BAe Systems	Adoption	Evaluation methodology	- Problem statement - Adoption of result - Industry expertise	Qualitative: - weighted scoring - portfolio matrix
TRM for Russian aviation industry (Vishnevskiy *et al.*, 2015)	Moscow School (ISSEK of HSE)	Russian state aerospace enterprises	Adoption	Roadmapping methodology (integrated technology roadmap plus foresight)		Qualitative: - weighted scoring - portfolio matrix
TRM validation (Geet et al., 2015)	GeorgiaTech	NASA	Adoption	Approaches to automated trend validation		Quantitative: - automated patent analysis - text mining - cluster analysis tec.
Product technology roadmap (Sourav *et al.*, 2018)	Portland State University/ Hamburg State Universit	Airbus	Adoption	Roadmapping methodology		Qualitative/ Quantitative: - SWOT - Quality Function

	y					Deployment - Analytic hierarchy process
Program/product technology roadmap (Cresto Alenia *et al.* 2018; 2019)	Politecnico di Torino	ESA	Collaboration	- Roadmapping methodology ("Technology Roadmapping Strategy") - Roadmapping automation solutions	Same, plus: - Joint methodology development and testing - Pilot use and validation (ESA H2020 STRATOFLY project)	Qualitative/ Quantitative: stakeholder analysis, a hierarchical multi-level functional analysis trade-off analysis
Program/product technology roadmap (Weck, 2022)	MIT / Skoltech	NASA	Collaboration	- Roadmapping methodology ("Advanced Technology Roadmap Architecture")	Same, plus: - Project management expertise - Access to statistics	Qualitative/ Quantitative: - Concurrent Design Facilities - Low-fidelity modelling

5. Contribution

The purpose of this study was to systematically analyze literature concerning mutual influence of existing roadmapping schools and aerospace industry.

The study contributes to the theoretical field by (1) characterization the current publication activity of aerospace in the field of TRM, (2) the identification of the two emerging roadmapping clusters and, finally, (3) by assuming the paths of assimilation of the TRM methodology from academic findings to the aerospace industry and vice versa.

First, despite direct evidence of the widespread use of TRM in the aviation industry, the number of publications in the scientific field continues to be persistently low, presumably due to confidentiality. The conducted bibliometric analysis shows that the total volume of publications on the application of roadmaps in the aerospace industry does not exceed 3% of the total number of publications on TRM, which is ~1% lower, but comparable with the result shown in the review by Ding *et al.* (2023).

Keywords analysis comparison between a set of 596 articles related to TRM in business, economics, and an aerospace-associated set of 17 articles allowed us to confirm the widespread anticipation that in aerospace the scope of TRM application of is focused mainly on issues related to scientific research and development, which is confirmed by subsequent coding and content analysis.

Regarding assimilation the study has indicated six cases of introduction of TRM-related approaches by the aerospace industry. The study ofthe mentioned casesmade it possible to assume the transit from an adoption of existing solutions towards roadmapping collaboration between aerospace structures and scholars.Moreover, analysis of the evolution of applied methods and approaches proves the tendency to further introducing quantitative approaches not only at the data collection stage, which is a long-lasting trend as in the "classical" academical TRM-related sphere (i.e. Lee, S., *et al.* 2008), but deeper into roadmapping development processes (e.g. Cresto Alenia, 2018; Knoll *et al.*, 2018; Viola *et al.*, 2020) and validation of roadmaps(Geet *et al.*, 2015).

Finally, this research made it possible to identify the two "emerging" centers of activity in the field of TRM development, not previously mentioned in literature reviews devoted to technological roadmaps: the ESA-Polito and one academic MIT-Scoltech, each of the recently made significant and presumably successful implementation of their TRM approaches into the ESA and NASA agencies, respectively.

Methodological contribution

Aside from the TRM-related results, this article may contribute to literature review methodology. Namely, it can serve as the case of identification of new "developing" TRM clusters became possible thanks to expanding the criteria used for the data collection in the engineering area. Therefore, it can be assumed that expanding the list of credible sources by criteria other than peer-reviewed in accordance with Ansoff's theory of weak signals (Ansoff, 1975) may increase the likelihood of obtaining meaningful results when conducting research based on literature reviews.Integrated analysis of two roadmapping data sets (business and economics; aerospace) and the precise author co-citation analysis allowed to identify the classical school of thought in TRM-field and to present the possibilities of classical approach application as for business as a whole and within the aerospace sector.

Practical contribution

Practitioners of the aerospace industry may find useful the approaches reviewed in this article as a source of best practices of development and implementation of technology roadmaps, as well as for understanding the evolution and recent trends in this area.As for instance, this study shows the possibility of quantitative and qualitative criteria application for developing roadmaps at different levels of decision-making and for choosing the most suitable approach for specific management tasks.

Directions of further research

This paper is considered as an initial part of the bigger research which aims to systematically describe the field of TRM applications in the production-related sectors of economy to find the field of possibilities for the on-going synthesis of the indigenous approach suited for application in Russian aerospace –S&T and/or R&D companies and divisions.

This study suggests that along with the widely used case study approach (Ding & Hernández, 2023), research into the experience of technology roadmaps in various industries may contribute to a better understanding of the assimilation of TRM-related body of knowledge, the specific features of the technology roadmapping process, and therefore, to create the prerequisites for the synthesis and generalization of best industry practices. Therefore, in the ongoing research it could be suggested to study the experience of using roadmaps in other industries, particularly in the field of applied science, research and development of complex technical systems. Additionaly, it could be interesting to investigate the potential of different roadmapping approaches implementation alongsideother methods of future study such as scenario planning tools, etc.

Limitations

Due to the limited number of publications within this study, this research does not provide evidence regarding the development of TRM in the aerospace industries of other major aerospace states as China, Russia, Turkey, India, and others. Besides the current political reasons, this presumably could be explained with high non-disclosure requirements combined with a lack of intention to international publishing. Thus, it may also be assumed that more research is required in the field of roadmap technologies in the EU, since this segment presumably remains not described in the reviewed literature.

7. Conclusions

Being initially developed and introduced by Motorola in the late 1970s (Willyard & McClees, 1987), technology roadmaps have now become a widely used strategic planning tool for technology development in many fields, including aerospace. In this study, Iattempted to identify the current trends in the development of roadmapping practices within the aerospace industry and, conversely, to examine which academic practices are being assimilated through a systematic review of the literature. This study is the first attempt to systematically find the actual interrelation between academics and aerospace industry regarding TRM development. The combination of systematic review methods including textual analysis for keywords and abstracts, the author co-citation analysis, and a manual qualitative thematic coding allowed us to describe the evolution of those relations. It indicated six cases of assimilation of the academic TRM-related approaches by the aerospace industry with a tendency of (1) strengthening the cooperation model between aerospace structures and scientists from the adaptation of ready solutions for joint development in the field of roadmapping, and (2) increasing efforts to integrate quantitative and qualitative approaches to roadmapping. Besides that, the author have identified Polito-ESA and MIT-Scoltech as the two “emerging” centers of activity in the field of TRM development, not previously mentioned in literature reviews related to technological roadmapping.

The results of the study may contribute scholars by distinguishing the previously underexplored recent aerospace-related TRM practices and emerging centers of thought, while practitioners may find it useful while estimating the option of collaboration with academical institutions in roadmapping sphere. Also, understanding of different approaches for TRM creation might be helpful for strategic innovation managers while implementingproduct or innovation strategies elaboration.

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