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Technology Roadmapping (TRM): a systematic review of the literature focusing on models

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ABSTRACT

The Technology Roadmapping (TRM) approach has been applied and disseminated among organizations of diverse sizes, from small enterprises to major government policy projects, to achieve an effective alignment of an organization's strategic objectives with technologies related to the products and considered key elements for the success of several businesses. Research has been done to contribute to new models of the TRM approach that can result in improved results for diverse applications. This work aims to carry out a systematic review of the literature, by mixing a bibliometric study with the analysis of networks and content on the connection between TRM and strategy, and to present a set of models associated to the theme. We highlight the bibliometric mapping of the article sample as the main contribution. In addition, analysis of clusters of citations and co-citations was carried out in order to present reviews of articles and authors identified to the models of TRM, with application comments.

1. Introduction

Established firms tend to make new product development decisions based upon the incremental return on investment, as well as their continuing marginal return on past investments. However, this way of evaluating the feasibility of new product development is inadequate to assess the full impact of a technology on current and future activities since the technology must be assessed with respect to the interactions with other technologies and with the system as a whole (Petrick and Echols, 2004). According to the same authors, balancing investments in current efforts while initiating efforts in new technology trajectories helps provide the needed cash flow to fund future work.

In large organizations there can be so many technologies used in different business areas that even the engineers may not be aware of all of them. When the same technologies are used in different types of products, knowledge about them can also be generated by various groups within an organization (Stig, 2013).

High technology firms face an environment characterized by frequent innovation, high mortality rates, high priority on research and development, stiff competition in a race to the marketplace, and partnerships with firms that may be potential competitors (Bilalis et al., 2002).

Considering the corporate strategy, Albright (2003) already pointed out that the technology roadmap or the TRM process, considered a support tool in the management and planning of technologies Phaal et al. (2004a), is used to define the plan for the evolution of a product, linking business strategy to the evolution of the product features and costs to the technologies needed to achieve the strategic objective. Geum et al. (2015), emphasizes this aspect of the strategic nature of the TRM, because in order to develop a TRM with good quality, there is a need for specialists of the organization to conduct subjective and qualitative tasks. Loyarte et al. (2015) have pointed out that the TRM is a strategic tool that can help organizations develop a vision from the outside in and challenge their current competitive perspectives.

According to Vatananan and Gerdsri (2012) the TRM process has aroused academic interest in the implementation and operationalization phases of the approaches. These authors also report a focus on research in the operationalization of the TRM process through the standardization and development of tools and techniques to aid in the analysis of technology. Carvalho et al. (2013) point out to the development of critical success factors for TRM and factors for its moderation. There is a lack of empirical evidence related to the influence of factors such as industrial sector, firm size, or other important moderator variables. These authors also point out the scarcity in the literature regarding situations of interface between TRM and strategic alignment and point to gaps related to the sustainability of the process in firms. Due to its characteristic high flexibility, TRM can be personalized for different applications (Dastranj et al., 2018; Ghazinoory et al., 2017;

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Phaal and Muller, 2007; Son et al., 2017).

Thus, in order to contribute to the research field, this work aims to carry out a systematic review of the literature, by mixing a bibliometric study and analysis of networks and content on the connection between TRM and strategy with a search for models in the ISI Web of Science database. The search for models of TRMs is what most differentiates this study from other review studies as seen on the chapter overview of the TRM. As a contribution, we sought to form a portfolio of articles aligned with the theme of the study, whose metadata were analyzed in bibliometric analysis software to generate clusters of articles and researchers. The results may help to explore the TRM theme, as well as, to show a set of TRM application models for different types of applications.

After this introduction, the article structure presents an overview of TRM, followed by the methodological procedures, as well as the presentation of the bibliometric results, discussion on TRM models, and the final considerations of the research and the bibliographical references.

2. Overview on TRM

Given that the priority of R&D projects and the interdependencies between the projects in a high tech firm change dynamically, high tech R&D project management is a complex and challenging endeavor (Verma et al., 2011). In this sense, term 'technology' is used by some researchers to refer to the product-defining technologies that establish the rules for an entire industry, such as digital camera technology, while others refer to the broader concept of technological knowledge as types of competence used for development and manufacturing (Stig, 2013).

The concept of technology used in this work is the broader concept, as mentioned above for manufacturing. As used by Stig (2013), the concept of technology in this work is that of dedicated efforts to create new knowledge to develop a particular technology for a certain field of application. In this paper, we present a new approach for the development and implementation of the Roadmap, which is a technique for supporting technology management and planning, especially for exploring and communicating the dynamic linkages between technological resources, organizational objectives, and the changing environment (Phaal et al., 2008).

According to Oliveira and Rozenfeld (2010), the technologies developed in an organization must be integrated into a structure that can consider the objectives and expected results. A technology roadmap, according to Phaal et al. (2001), has the ability to show the interrelationship between market, product, and technology and has been applied in a large number of industries. According to the latter author, a technology roadmap has a visual model, related to the other product projects of the organization.

The roadmap process takes place at a time of strategic planning and after iterations, or years of use and refinement, begins to coordinate with an organization's technology strategy. The roadmap process begins at a time prior to the project portfolio definition, as a key step in the implementation of the project portfolio strategic planning process (Phaal et al., 2005).

According to Groenveld (1997), in order to define the products in terms of customer requirements, a good understanding of markets and applications is required. He states that from these requirements, the technical product functions are determined, followed by the technologies needed to realize these functions.

The particular feature (and benefit) of the technology roadmapping concept is the use of a time-based structured (and often graphical) framework to develop, represent, and communicate strategic plans, in terms of the coevolution and development of technology, products, and markets. (Phaal et al., 2004a).

2.1. Review studies on TRM

Previous studies focusing on review of TRM theory based on systematic bibliometric and content analyses were released in the academic field. In a review study on TRM, Park et al. (2009), analyzed papers from 1999 to 2009 and classified them according to various criteria in order to understand the critical issues regarding how, for what purpose, and in what area the TRM´s are present in the literature. The authors were able to identify that more empirical research on TRM was required and that the development of TRMs for the purpose of the asset of knowledge and integration planning should be encouraged. In the same vein, Choomon and Leeprechanon (2011), after a short review on TRM and a more detailed application study on a specific field, noted limitations in the literature regarding TRM integration.

Vatananan and Gerdsri (2012), covered 172 papers related to TRM from 1987 to 2009, in the major journals and conferences focusing on management of technology and innovation. The authors identified that "keeping the roadmap alive" was the key challenge in the field and that this challenge could be addressed by means of working on the effective operationalization and implementation of TRM´s. In a literature review focusing in the relationship between TRM and SMEs (Small and Medium Enterprises), Arshed et al. (2012), found a scarcity of studies addressing involvement of SMEs in the TRM process. The study also suggests the involvement of the government as a *mechanism for engagement on SMEs in the TRM process*.

In a literature review of TRM, Carvalho et al. (2013) reported an increase in TRM studies over time and that TRM is still in an exploratory phase of research. The study also indicates that the interfaces between roadmapping and other initiatives considered vital to innovation, including knowledge management, communication skills and strategic resources and competences, are little studied in the literature.

Focusing on publications addressing concerns with the development, implementation, and operation of TRM, called concept publications, Gerdsri et al. (2013), gathered 229 papers from 1987 to 2010, and proceeded to a bibliometric analysis on TRM. The authors concluded that most of the articles have been published since the year 2000 and are concentrated in three major knowledge disseminators: the Portland Intl. Conference on Management of Engineering and Technology (PICMET) as well as the journals Technological Forecasting and Social Change and the Research Technology Management. The authors also concluded that the use of bibliometric and patent analysis for the TRM development, decision support for operationalizing the TRM process, and the visualization of a TRM architecture would be emerging issues regarding the TRM.

In addition, Zamberlan (2014), reviewed TRM focusing in the strategic trends and patterns in the automotive and consumer wireless technologies. The systematic review on literature searched published studies from 1997 to 2013, collecting 105 publications aligned with the theme. Although the author could find only a few review articles addressing automotive or wireless areas, it was possible to separate the papers according to clusters related to the keywords of strategy, trends and positioning.

Finally, Letaba et al. (2015) analyzed TRM literature from the years 2000 to 2013 to be able to measure the evolution of what was called the TRM generations: first generation TRM (focus on product technology roadmap), second generation TRM (focus on emerging technology roadmap), and third generation TRM (focus on innovation roadmap); the study reveals that a strong co-evolution of all the three generations of TRM had happened, and a growing interest in emerging technology roadmapping confirms the complexity of the technology innovation nowadays.

3. Methodology

According to the methodology framework presented by Eduardo Tasca et al. (2010), this study is characterized as: theoretical, by the nature of the articles and descriptive by the nature of its objective, with inductive research logic. The research process used secondary data, with a qualitative-quantitative approach. For this, the method of systematic literature review was used, combining bibliometric research, network and content analysis.

Bibliometric research and network analysis were done with the VOSviewer software tool, which is widely used and allows to generate easy-to-interpret bibliometric maps (van Eck and Waltman, 2010). Still according to van Eck and Waltman (2010), the software has also been used in several projects with successful results.

The systematic review of the literature used the ISI Web of Science base, which according to Carvalho et al. (2013), in addition to enabling research on its own base, searches for articles that are also included in other relevant databases, such as Scopus, ProQuest and Wiley. In addition, the ISI Web of Science base allows for the extraction of metadata information, such as abstracts, citations from authors, which are required for the analysis proposed in this article and accepted by VOSviewer software.

The search was limited to articles published in Journals and/or presented at conferences. In this way, the articles can be considered better quality ones due to the evaluation by peers. The articles were also in English language, for publications starting from 2002, resulting in a total of 273 articles. After an individual assessment by reading for alignment to the topic relevance in the titles and abstracts, we gathered 102 articles aligned with the theme. In addition to this portfolio of articles in the database, other papers were included after the snowball process obtained from the reading of the original 102 articles in the portfolio of articles, totalizing 124 articles in the final sample, according to Fig. 1.

The final portfolio of the selected articles (124) was analyzed for the trend (distribution of articles for the year in which they were published), internationality (distribution of articles by country, according to the main author) and source (journals or conferences in which they were published). The portfolio article metadata was generated and exported from the database for network analysis with the VOSviewer software. The network analyses included the occurrence of keywords to determine the main connections between words and co-citations of authors and to analyze clusters of authors, focusing on models of TRM and gaps for future research. Through the metadata, analyses of citations of the main articles were also generated. The most cited articles were evaluated for the proposed TRM models.

4. Results and discussion

4.1. Literature measurements

The trend of sample publications can be seen in Fig. 2. A dotted line was drawn to facilitate viewing the evolution of the number of articles in the article portfolio over the years. There has been an increase in the number of publications over the years. In an initial period, between 2002 and 2006, few articles were generated from the portfolio of articles related to this study. Most of the publications were made between 2007 and 2010. Starting in 2013, there is a new increase in the articles aligned with the theme of this study, taking into account that the data were collected until the end of October of 2017.

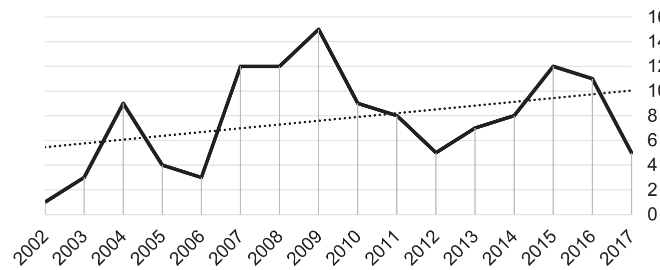

Fig. 2. Number of articles and year of publication.

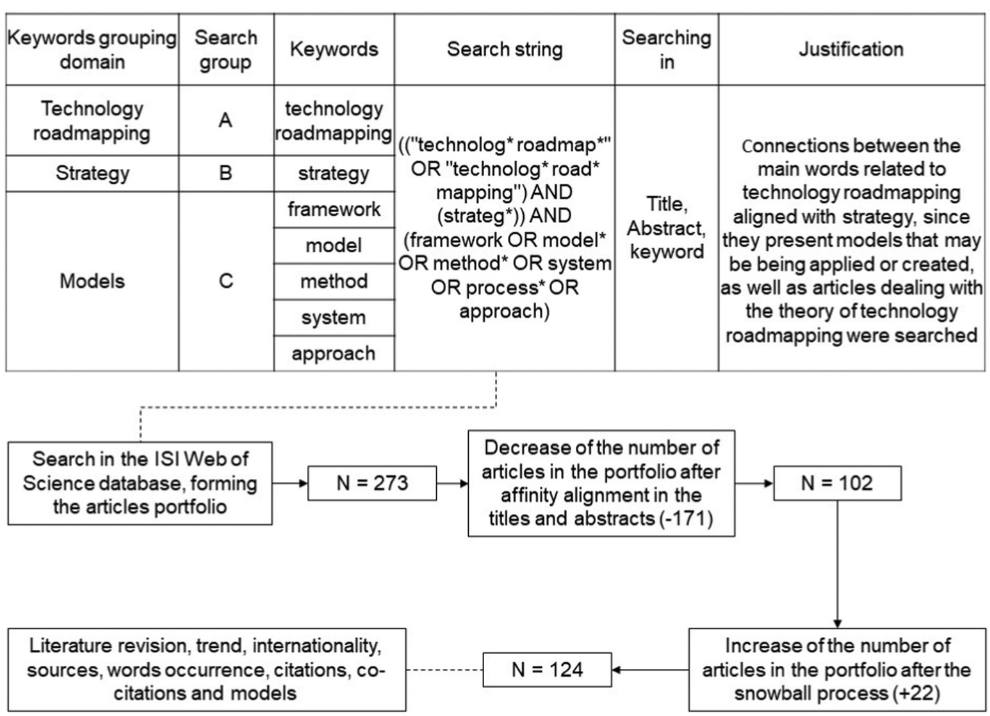

Fig. 1. Search steps for construction of the article portfolio.

The analysis of the internationality of the articles in the sample, as seen in Fig. 3, clearly shows a predominance of authors from England, South Korea and the USA. About 60% of the articles come from authors from all three countries.

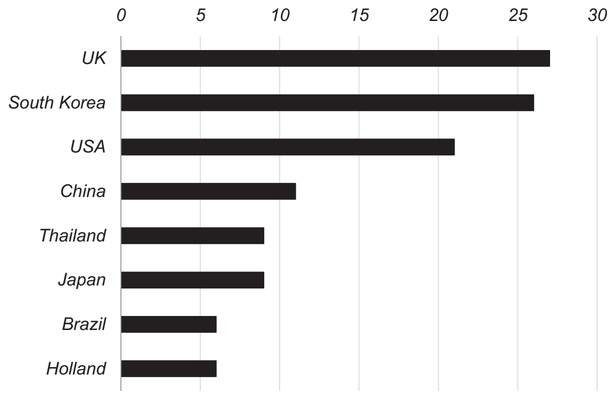

Fig. 3. Number of publications per country (≥6).

Fig. 4 lists the sources (journals or conferences) that had five or more articles in the article portfolio of the present study. There is a large predominance of publications in two sources, the Technological Forecasting and Social Change magazine and the PICMET conferences - Portland International Conference on Management of Engineering and Technology. These two vehicles concentrate around 54% of the publications.

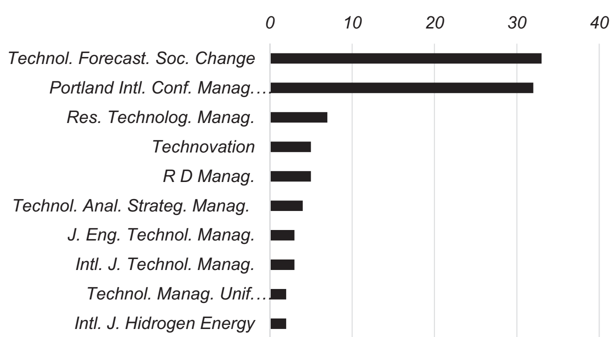

Fig. 4. Articles sources (≥5 articles).

Authors' affiliation, i.e. institutions whose authors (first authors) publish the most in the portfolio of articles in this study can be seen in Figure 5. The two main clusters are at Cambridge University, England, and at Seoul National University, South Korea. About 46% of the articles in the article portfolio of this study originate in these two institutions.

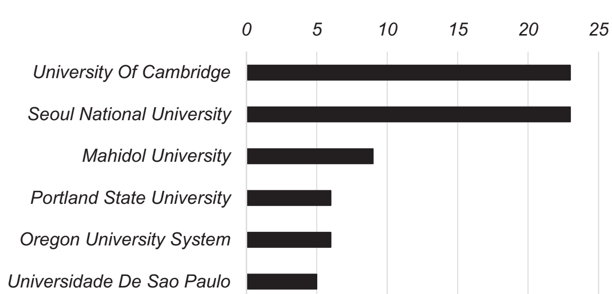

Fig. 5. Authors affiliation (≥5 articles).

The leading authors (first author of an article) of the articles in the sample of this study are shown in Fig. 6. The top eight authors account for 67% of articles in the article portfolio of this research.

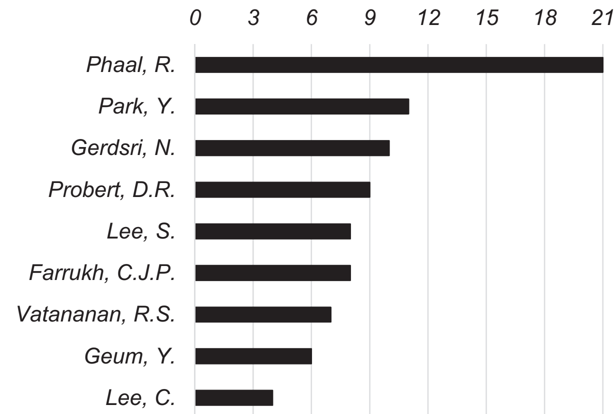

Fig. 6. Main authors (≥4 articles).

4.2. Network analysis

The frequency of citation of a word in the articles allows for a first reading of the themes in one area (Thomé et al., 2016). Within 433 words citation in the 124 articles, twenty-five (25) words have been cited more than six (6) times. The keywords that originally were part of the database search were then removed from the analysis, as shown in Fig. 7. The link between the words also shows the connection between them in the articles collected.

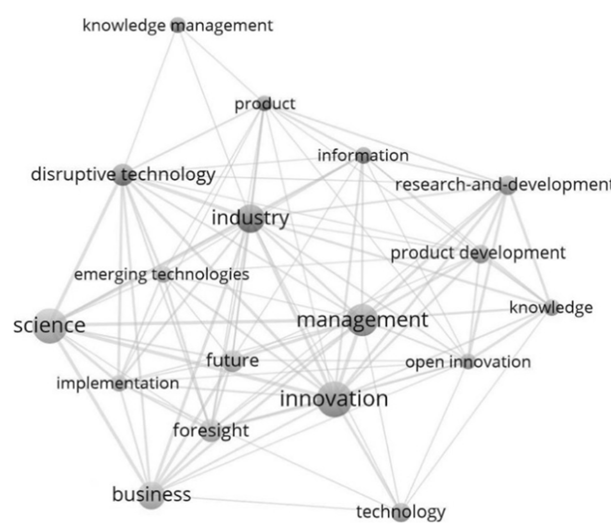

Fig. 7. Occurrence of words – network map.

4.2.1. Citation clusters analysis and roadmapping models

The citation information of the main articles is arranged in the network map in Fig. 8. It is also seen that there is a predominance of five clusters of more influential articles in the base – for articles with a number greater than or equal to 20 citations. The number of citations indicates the influence of the article in the database and refers to the total number of citations within the database, as these are part of the metadata extracted from the database.

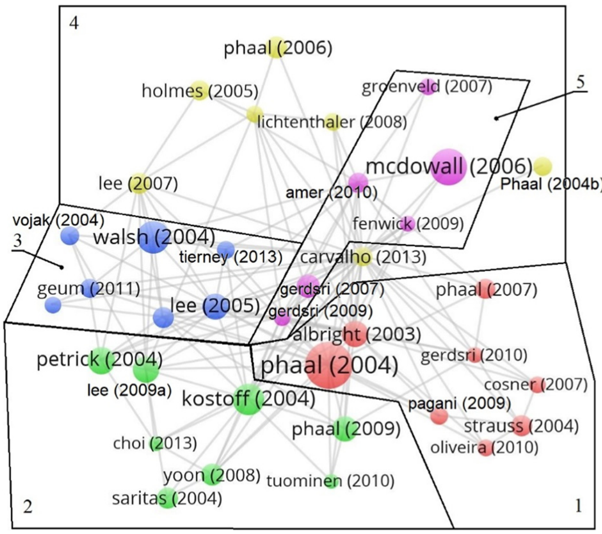

Fig. 8. – Citation of articles in the database, with network map.

In citations Cluster 1, Phaal et al. (2004a), the most cited article in this study, proposes the method named T-Plan fast-start for TRM. This method, developed in collaboration with the industry, provides a means to understand the architecture of roadmaps as well as a rapid initiation into the process in a variety of organizational contexts. This method supports the initialization of the roadmapping process, establishing important links between technology resources and business drivers, identifying important gaps in the market, product, or technology, and developing the first view of TRM.

When added with patent analysis techniques, the roadmapping can improve the objectivity and reliability of technology roadmaps, as concluded by Lee et al. (2009a). In the same cluster, Strauss and Radnor (2004) proposed a methodology that combines Scenario Planning with TRM. When combined and applied in particularly dynamic and volatile environments, scenario planning, with its improved vision, flexibility and environmental forces monitoring features, and TRM, – with its characteristics of clarity, integration and attention to details can allow teams and organizations to achieve better results in planning their technologies.

Phaal et al. (2007), when studying the communication associated with the development and dissemination of roadmaps, particularly for the alignment of technologies with commercial perspectives, proposed a methodology based on workshops to support the identification and exploration of strategic issues and opportunities as part of the T method -Plan fast-start.

In a 3G mobile TV TRM study, Pagani (2009) applied the SEARCH (Scenario Evaluation and Analysis through Repeated Cross Impact Handling) approach. This approach is widely used to estimate the impact of different policies on the evolution of a scenario and to assess any risks associated with competitive strategies under different future conditions. The central idea of this approach is the assumption that a single event, which requires planning, can be impacted by other events. Expert experience is gathered in the form of subjective probabilities and later simulations and mathematical techniques are used to generate other scenarios.

Oliveira and Rozenfeld (2010) developed the Integrated Technology Roadmapping and Portfolio Management (ITP) method, which explores the complementary characteristics between TRM and Project Portfolio Management (PPM) to support the initial phase of the new product development process. The ITP method comprises a flow of activities that begins with the activities related to the TRM, followed by the activities of the process of "Proposals for new projects", and finalized with the activities of PPM.

Still in Cluster 1, Cosner et al. (2007) investigated how to integrate TRM into organizations with multiple business units and what the benefits of TRM coordination for all these units are when done in a unified way. Three crucial steps were pointed out by these authors for the integration of technical planning of the technologies: first it is necessary to establish the objectives of the roadmapping process; a second step is to determine the approach that is appropriate according to the culture of the organization and thus will be used to build the roadmaps (build from the core group, using the information collected in the organizational units, build from a series of workshops with different stakeholder groups, or build from the contribution of each of the business units); the third step is to establish the architecture of the roadmap, i.e. how a roadmap of the organization will be broken down into individual plans.

In order to propose a TRM implementation guide, Gerdsri et al. (2010), applied the Change Management approach to the three stages of TRM implementation in an organization: initiation, development and integration. The proposed action plan can help through the necessary changes for the implementation of TRM.

In Cluster 2, Kostoff et al. (2004) proposed a systematic approach using TRM techniques to identify potential disruptive technologies and products that would have the potential to redefine an entire industry or even create a completely new industrial area. In another study, Petrick and Echols (2004) proposed a heuristic approach with TRM so that companies can plan new technologies and markets, and thus, new product priorities in the long-term.

It was already noted by Albright and Kappel (2003), that roadmapping can identify and help focus product strategy and development on the few elements of greater importance to success. According to these authors, the technology roadmap can help identify common needs and opportunities for technology reuse. Phaal and Muller (2007), consider that there are already several approaches to the TRM process, but with few studies that help define the basis and conceptualization of the process, they have sought to contribute to the architectural aspects essential for the execution of roadmaps.

Yoon et al. (2008) proposed an approach that makes it possible to deal with radical or incremental innovations through the technique known as text-mining, text analysis in technological documents. In order to overcome the challenges introduced by the multidimensional characteristics and complex nature of technology forecasting studies, Saritas and Oner (2004) proposed the combination of two methodologies: Integrated Management Model (IMM) and roadmapping, IMM has benefit of being able to analyze long-term normative policies and what would be needed in terms of transformations and changes in the organizational structure and behavior, and the roadmapping would allow for the capture, manipulation, and management of information to reduce the complexity of the future planning of the technologies.

Choi et al. (2013), proposed a quantitative approach to TRM through the use of text-mining, a process by which high quality information can be obtained from texts to extract SAO (Subject-Action-Object) structures in the database with patent information. This approach allows R&D managers to extend their visions of products and technologies during the development of a TRM.

In a context of transport systems analysis, Tuominen and Ahlqvist (2010) applied TRM to consider social and technical aspects through the combination of layers of the roadmap related to science and technology. In this study, five layers were used: user needs, markets, actors, technologies and assessment knowledge. This approach proved to be useful as it has generated relevant knowledge in five different perspectives.

In the Cluster 3, Walsh (2004) proposed a TRM focused on improving the systematics for disruptive technologies. In disruptive technology cases, there are several other stakeholders involved, and time is critical. This method seeks to increase the execution speed of disruptive technology planning. In other research, Lee and Park (2005) proposed a roadmap customization model to obtain a good balance between complete personalization and complete standardization of roadmaps. Lee et al. (2013) used a hybrid methodology for TRM incorporating Quality Function Deployment (QFD) to establish interconnections between services and devices and between devices and technologies in Smart Cities planning. The QFD aligned to the TRM allowed a realistic view due to its pictographic representation.

Geum et al. (2011) suggested a new type of roadmapping process through the incorporation of product-service integration into traditional TRM. They suggested six types of integrated roadmaps, according to the relationship between the product/technology/service: technology with an enabler (direct or indirect integration), technology with a mediator (servitization or productization) and technology with a facilitator (services or products). In a case study in the area of health services, Geum et al. (2011) have shown that the technology features of the technological components affect both the products and the services and that this can be strategically planned in an integrated roadmapping.

The study by Vojak and Chambers (2004) suggested the SAILS (Standards, Architectures, Integration, Linkages, Substitutions) method as a methodology with a systematic approach to the prediction of disruptive technologies, as opposed to the development of technologies in stable areas. In this study, a wide range of disruptive opportunities and threats were identified during the TRM process using the SAILS methodology in three application examples.

Tierney et al. (2013), proposed a TRM method called Technology Landscaping, which aligned with the specifics of the pharmaceutical industry, and allowed that the mature restrictions of the technology, the existence of consortia as a concept of interested parties, and the dynamic changes of the technologies can be included in the analysis.

In addition, An et al. (2008) developed a TRM approach, which included QFD quality tool analysis to support the traditional TRM approach, which is focused on product-service. This approach allowed segregating product-related dimensions from the service-related dimensions, allowing for more detailed information and facilitating understanding of the roadmap.

In Cluster 4, Phaal et al. (2006) developed what they called a management tools catalog, to help managers in organizations effectively manage technologies that benefit business. Lee et al. (2007) proposed a new systematic method called TechStrategy for the construction of TRM for R&D purposes, with good results in practical application. The study of Holmes and Ferrill (2005), proposed a variation on the fast-start T-Plan methodology, called OTR (Operation and Technology Roadmap), including elements of analysis of soft issues (such as technology management) and would be applied in the initial challenge, before the first TRM workshop.

Another methodology was developed by Phaal et al. (2004b) to support the practical and theoretical understanding of the management of technological innovations. The methodology takes into account two aspects of the management of technological innovations: processes of core strategies and support processes for technology management. This methodology helps to integrate the two strands by focusing on the flow of the push and pull knowledge that occurs between the commercial and technological functions of an organization.

Lichtenthaler (2008) demonstrates the importance of the TRM process being aligned with the organization's strategy and extending the process of roadmapping for external exploitation of the generated technologies. For example, roadmapping can consider the potential financial return of the technology as a product to be sold.

Observing a gap in TRM concerning its application in the technology-push commercial strategy, Caetano and Amaral (2011), proposed a method named Method for Technology Push (MTP) that would better suit the demands of this strategy. This method presents as an improved feature, the systematization in the adoption of partnerships according to the needs of the resources. MTP has real applications for Small and Medium-Sized Enterprises (SMEs) and independent research centers in open-innovation environments.

In the citations Cluster 5, McDowall and Eames (2006), considering TRM as being of vital importance for future technologies, surveyed the technology roadmap (among other techniques) as a tool to show the research and to see graphically what the future markets, technologies, and policies related to the hydrogen economy would look like.

Gerdsri and Vatananan (2007) concluded that using the Analytic Hierarchy Process (AHP), which is a method to aid in complex decision making, both the intangible and tangible impact of technologies on a roadmapping can be measured. In this study, the roadmapping process was reinforced by introducing flexibility, dynamics and operational characteristics in the analysis through the development of the Technology Development Envelope concept. In this concept, the re-assessment of technology values can be done in three ways: changes in the development of a particular technology are captured, new technologies emerge, and changes in the organization's priorities are identified.

In another study, Amer and Daim (2010) surveyed the use and application of TRM in the renewable energy sector and concluded that TRM has been widely used in the renewable energy sector, and results have been different for roadmaps according to the level of application: national, industry/sector and organizational. The objectives of the TRMs in this sector arefocused on obtaining a consensus among the various stakeholders, creating a common vision, defining guidelines for government agencies and decision makers, establishing objectives, identifying markets and barriers, formulating strategies, among others. The authors have identified several approaches to TRM or hybrid approaches applied in renewable energy studies, such as patent analysis, QFD, Delphi method etc.

Gerdsri et al. (2009), analyzed the dynamics of TRM implementation in organizations and showed that the TRM process is complex. Clarifying the roles and responsibilities of each participant is vital for the successful implementation of TRM, especially the participation and involvement of key members during implementation phases.

According to Groenveld (1997), the process of roadmapping contributes to the integration of business and technology and to the definition of technology strategy by displaying the interaction between products and technologies over time, taking into account both short and long-term product and technology aspects.

Fenwick et al. (2009), presented a new approach to TRM through the integration of marketing techniques and decision methodologies as a counterpoint to more traditional methods applied to products that represent a unique ROI (Return on Investment). This approach would be responding to a gap in the research related to completely different business and financial models that center on licenses and signatures such as web services.

4.2.2. Co-citation clusters analysis and roadmapping models

The eleven (11) most relevant articles analyzed have citation numbers greater than or equal to 50. Fig. 9 shows the evolution of the trend of citation of these articles over time. 1116 quotes from the 1975 citations of the 124 articles in the portfolio of articles in this study (about 57%) are among the 11 most relevant articles. There is a relevant concentration of articles led by Professor Robert Phaal from the University of Cambridge, a major research center on roadmapping. His articles, eleven (11), account for 24% of the quotes within this portfolio of articles.

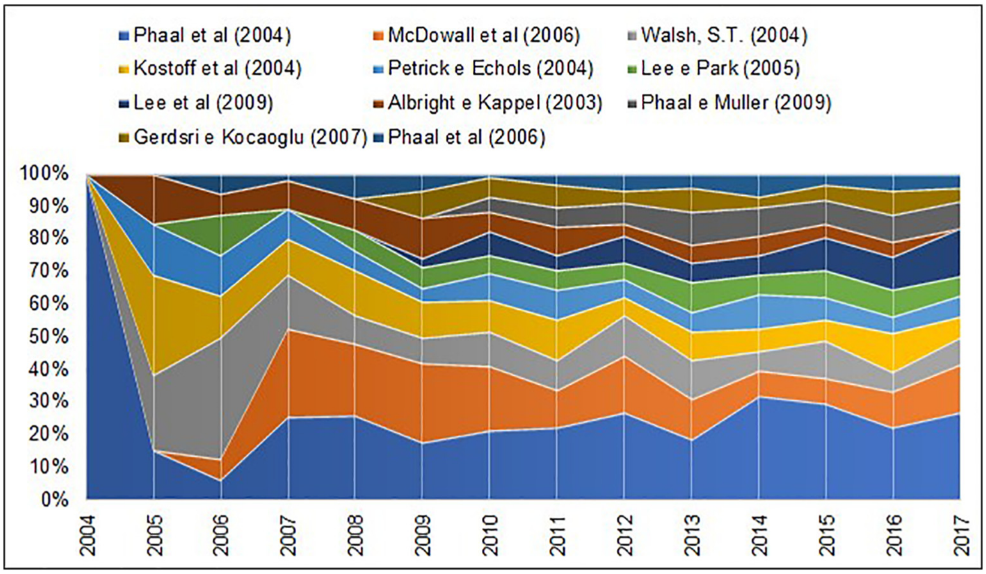

Fig. 9. Evolution of the citation trend of the eleven most relevant articles.
Note. Reading from the left, the vertical line corresponding to each year indicates, by the crossing with the distribution line of each article, the percentage of citations of each article in that year.

The co-citation information, through the map of authors' network, is shown in Figure 10 for the authors cited in the articles. A minimum co-citation number of 20 per author was used. The authors' connection is determined based on the number of times they are cited together, meaning that the authors of the portfolio articles are considered relevant knowledge of articles when generated by the authors of each cluster of co-citations. This means that they have been researching similar subjects or in related areas, generating citations from other researchers in the same articles. There is a predominance of three clusters of co-citations.

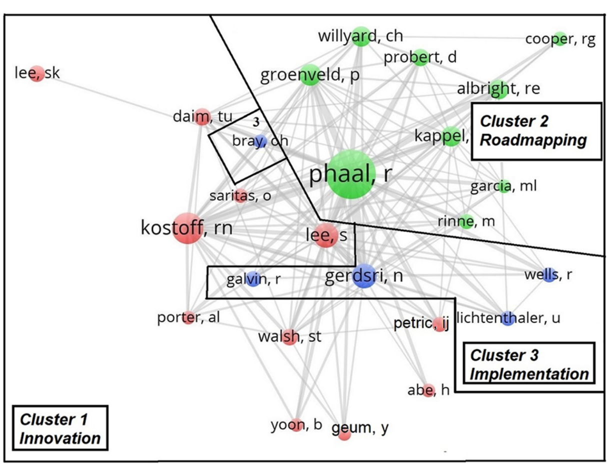

Fig. 10. Authors' co-citation in the database – network map with cluster indication.

The link between the authors shows that they were cited in the same article in the portfolio and the intensity of the line connecting two authors corresponds to the intensity of that relationship. In Table 1, the division of the clusters of the authors of the articles of this study is shown. The values of link intensity refer to the intensity of the author's relation in the set of articles in the portfolio. Through the gaps of the main clusters, the relevant themes for present and future research in the theme can be foreseen.

Table 1
Authors' cluster of the article portfolio.

Author	Citations	Link intensity	Cluster
Abe, H.	21	286	1
Daim, T.U.	34	632	1
Geum, Y.	20	331	1
Kostoff, R.N.	123	1536	1
Lee, S.	76	1249	1
Lee, S.K.	32	78	1
Petrick, I.J.	25	443	1
Porter, A.L.	22	430	1
Saritas, O.	23	450	1
Walsh, S.T.	32	573	1
Yoon, B.	22	399	1
Albright, R.E.	45	602	2
Cooper, R.G.	24	245	2
Garcia, M.L.	22	447	2
Groenveld, P.	58	879	2
Kappel, T.A.	48	682	2
Phaal, R.	323	3649	2
Probert, D.	36	553	2
Rinne, M.	27	446	2
Willyard, C.H.	47	571	2
Bray, O.H.	21	413	3
Galvin, R.	28	393	3
Gerdsri, N.	76	1620	3
Lichtenthaler, U.	26	381	3
Wells, R.	25	400	3

Cluster 1, renamed by the word innovation, contains authors who somehow use roadmapping as a tool for evaluating innovative, disruptive, or emerging technologies. These authors applied multiple techniques, such as TRM combined with others, to improve the evaluation of emerging technologies in various fields of activity. Some of the main articles of these authors are mentioned below:

Daim et al. (2006), demonstrated that the results of the technology forecast can be improved through the integration of multiple methodologies, and in line with this subject, Geum et al. (2013a) developed a methodology for identifying and selecting strategic R&D partnerships through an index-based approach using a combination of patent analysis and review of publications.

Kostoff and Schaller (2001) concluded that roadmaps for S&T

(Science and Technology) should allow planners the ability to perform capacity-sensitive studies of project programs, allowing the planner to have the flexibility to change parameters at any node in the roadmap network, and roadmaps for the technical areas should cover all S&T-related project programs, because once incomplete or restricted, a S&T roadmap would generate a fragmented picture in which gaps might not actually exist.

Lee et al. (2009b) proposed a new approach to create and use keyword-based patent maps in creating new technologies. Text-mining was used to transform patent documents into structured data to identify keyword vectors, followed by the analysis of the main components to reduce the number of keyword vectors, to be able to view information on a two-dimensional map, and finally to identify the "vacancies" of patents, represented as the blank areas in the two-dimensional map as trends in patent densities.

Cluster 2, or Roadmapping Cluster, contains authors with relevant research related to roadmapping process theory. Some of the main articles of these authors are mentioned below:

Willyard, C.H. and Groenveld, P. were pioneering authors in applying technology-aligned roadmaps to companies, the first in Motorola Inc. in the USA and the second in Philips Electronics in the Netherlands. For Willyard and McClees (1987), technology roadmapping was considered a corporate process that could help reduce the potential risk of neglecting some important elements of new technologies in new products and processes due to the increase in complexity that has occurred over the years. For Groenveld (1997), the TRM should be seen as an ongoing process that is part of the business cycle.

The most cited author in Cluster 2 - Roadmapping, Phaal, R., is also the most cited in the research on the theme and coordinates the research group in process Roadmapping at University of Cambridge, UK. Phaal et al. (2003), describe the T-Plan, which is a method for quick start of the roadmap process in organizations. The T-Plan involves a series of facilitating workshops to ensure that technology and new product developments decisions are aligned with the products planning and that this planning is also aligned with the strategic needs of the organization. Phaal et al. (2005), propose techniques to identify and evaluate suggestions for creativity, communication, and decision-making in common workshops in roadmapping processes, in addition to its T-Plan method.

In Cluster 3, or the cluster of "Roadmapping Implementation", the main author, Gerdsri, N., by the number of intensity of the link, has research focused on implementation of roadmapping, with proposals for new approaches for implementation. Some of the main articles of the authors are mentioned below:

Gerdsri and Vatananan (2007) showed that the critical factors for the successful initiation and implementation of TRM in organizations are people, processes, and data. They concluded in this study focused on the people factor that it is essential to involve key people in the organization at different levels in the functional departments. As dynamic linking and the relationship between individuals and groups are strengthened, knowledge can be more effectively distributed and transferred.

In addition, Gerdsri et al. (2009), pointed out that with the completion of TRM implementation, any organization can claim that technologies and infrastructure will be ready when needed. Implementing TRM as a part of business strategy is challenging because it can affect the process of organizational work, structure, and culture. Bray and Garcia (1997) concluded that information on the need to perform a TRM, analysis on the need, and the alternatives of technologies are much more important than following an accurate roadmapping process.

A relevant portfolio of articles that relate TRM theory and practice was generated in the research. Table 2 shows a summary with comments on the models of articles with models from the portfolio that where not discussed in the main text.

Table 2
Comments on the models of the articles with models from the portfolio not discussed in the main text.

Authors	Context or application	Comments on the model
Abe et al. (2009)	Industry R&D	IST - Innovation Support Technology: Integration of Business Modelling and TRM. Through a combination of existing strategic TRM, Business Modelling, and a workshop approach TRM, the ISRM - Integrated Strategic Roadmap is built
Ahlqvist et al. (2012)	Systemic policy contexts	IPRM Innovation Policy Roadmapping: The method combines TRM with the systematic characteristics of science, technology, and innovation policies
Aleina et al. (2017)	Space exploration	Technology prioritization methodologies have been developed in support to the TRMs, in order to provide instruments to rank non-quantitative factors. Prioritization's criteria, cost-effectiveness, and risk are elements of analysis
Battistella et al. (2015)	SME	EM - Extended Map: The methodology was designed to meet the SMEs specific needs to support their decision in technologies. It helps the SMEs in order to facilitate the process of knowledge and openness to collaboration
Carayannis et al. (2016)	STI - Science, Techn., Innovation	Smart Roadmapping for STI Policy: Due to the complexity for STI roadmaps, using an open innovation approach, the model allows the integration of policy decision making and implementation of STI strategy level
Castro Gama and Guemes-Castorena (2014)	Medium sized organizations and business units	The sequential model with steps facilitates the creation of TRM at a functional level
Cheng et al. (2014)	RFID	HRMM - Hybrid Roadmapping Method: Incorporates inside-out and outside-in perspectives into TRM through a flow of information in a series of roadmaps
Cheng et al. (2016)	Testing, inspection and certification	SBRM - Scenario-based TRM: Proposes a practical scenario-based approach TRM, allowing the insertion of scenario into roadmaps at the organizational and operational levels
Dissel et al. (2009)	Early-stages technologies	VRM: Value Roadmapping is a workshop-based approach that combines cross-functional perspectives with supporting communication, in particular between technical and commercial teams
Authors	Context or application	Comments on the model
Featherston et al. (2016)	Emerging technologies	The framework based on TRM is designed to facilitate understanding regarding where standardization is important in emerging technologies
Fleury et al. (2010)	Educational technology services	The framework uses portfolio management techniques to identify the most relevant portfolio of technologies services
Fujii and Kawa (2008)	Chemical company	A customized TRM method is proposed using workshop TRM approach and KJ method, a popular method of idea creation in Japan
Gerdsri (2007)	Emerging technologies	TDE - Technology Development Envelope: TRM associated with multi-criteria decision-making methodologies Delphi method and HDM - Hierarchical Decision Modeling
Gerdsri and Kogaoglu (2007)	Eletronic cooling technologies	TDE - Technology Development Envelope: TRM associated with AHP, since it allows for the measurement of the impacts of technology on intangible and tangible aspects

(continued on next page)

Table 2 (*continued*)

Authors	Context or application	Comments on the model
Geum et al. (2013b)	Open innovation	The proposed approach for a dual TRM integrates a dual layer structure of internal and external resources
Geum et al. (2014)	Car-sharing/scenario planning	The approach combines integrating system dynamics and TRM to support the scenario planning
Geum et al. (2015)	Bibliometry	ARM (Association Rule Mining) based TRM: The data-driven TRM is developed using the ARM, which allows for the capture the dependent information between layers in the TRM
Ghazinoory et al. (2014)	Wind Energy	Integration of Fuzzy PROMETHEE with TRM: The approach focusses on the integrating decisions in roadmapping, i.e. between layers of the TRM
Ghazinoory et al. (2017)	Developing Countries Industries	Learning-based TRM: The method has an emphasis on challenges to create demands in the market, with attention to increasing the level of capabilities
Gindy et al. (2008)	Technology acquisition	STAR - Strategic Technology Alignment Roadmapping: The methodology, available in a specific software, uses several techniques to provide an integrated framework
Gonzalez-Salazar et al. (2016)	Bioenergy in devel. countries	The method comprises a known energy TRM framework aligned to a strategy based on Delphi to build consensus and an analytical modeling for expert judgment
Authors	Context or application	Comments on the model
Guemes-Castorena and Toro (2015)	Beverage dispensing system	Integration of Business Model Canvas and TRM: The method gives the TRM process the perspective of future analysis and also the capacity of visualizing elements for the current business. The time perspective of TRM complements the BMC results
Han et al. (2007a)	New product development	A systematic collaborative knowledge creation roadmap with layers is proposed to use TRM as a tool for the knowledge creation
Han et al. (2007b)	Knowledge mgt/engineering projects	The knowledge TRM process is composed of three stages: preparation from experts, workshops and implementation
Jeon et al. (2011)	Semiconductor	The model considers a fourth layer on the TRM regarding the equipment supplier, and this layer is evaluated using AHP
Jeong and Yoon (2015)	Patents	The Patent Roadmap is created based on TRM and has the feature of technology planning by analyzing the patent patterns development in analogous and targeting technologies. The roadmap uses patent analysis, text mining, TEMPESTE, and SCAMPER as tools
Kim et al. (2016)	New product development	Design Roadmapping Framework is a graph that positions expected core user experience and design elements along a timeline and then associates them with products, services, or systems
Lamb et al. (2009)	Energy/Wood	TRM associated to SWOT and QFD: the TRM was applied using SWOT and QFD for market drivers and product
Lee et al. (2009c)	Energy sources	MCDM - Muti-Criteria Decision Making using AHP and Fuzzy: reflects qualitative information from expert opinions efficiently
Lee et al. (2010)	Scenario planning	The approach combines a Bayesian Belief Network (BBN) into the TRM. The advantage of the BBN is to model and allows for the analysis of a complex problem common in scenario TRM
Lee et al. (2011b)	Hydrogen	Hybrid multi-criteria approach using AHP and DEA: conceptual study on the application of TRM related to the future of hydrogen
Lee et al. (2011c)	Hydrogen energy	MCDM - Multi-Criteria Decision Making using AHP and Fuzzy: reflects qualitative information from expert opinions efficiently
Lee et al. (2015)	Photovoltaic cell/Scenario planning	The systematic approach to make scenario-based TRM more robust by adding the ability to assess the impacts of future changes on organizational plans
Authors	Context or application	Comments on the model
Lee and Geum (2017)	Healthcare services/Scenario planning	A scenario-based TRM associated with Cross Impact Analysis (CIA), for the market layer, and the Analytical Hierarch Process (AHP), for product and technology layers
Li et al. (2015)	Solar cell	The bibliometrics method is applied to analyze the existing position of science and technology, and TRM workshops approach is applied to strategize and plan the future development of the technology
Ma et al. (2006)	Knowledge management	The methodology uses principles of interactive planning in phases to build a knowledge roadmap
Musango and Brent (2015)	Solar aided power generation	The proposed framework uses the results of literature review, trends, drive indicators, cost, and SWOT analysis
Richey and Grinnell (2004)	Motorola	ERMS - Enterprise Roadmap Management System: it shows how TRM evolved in the Motorola company and the visual and easily accessible status in the digital system of TRM available, with database of roadmaps
Scalice et al. (2015)	Durable consumer goods	TRM-MD - Modular Deployment: the method allows a company to plan module releases instead of products using a TRM structure. The reuse of information is facilitated due to the use of functions instead of components in the TRM
Siebelink et al. (2016)	Construction firm/Scenario planning	Scenario-Driven Roadmapping: the method combines scenario planning and TRM. The result is a TRM which incorporates scenario analysis. It is based on the T-Plan TRM approach.
Suh and Park (2009)	Technologies for service	SoTRM Service-oriented TRM: the framework contains a patent map followed by a priority analysis of technologies, and finally a construction of the service-oriented TRM
Suharto (2013)	Scenario planning	A multi-scenario based TRM using Bayesian causal maps with a systematic probability generation method
Trappey et al. (2017)	Logistic services	The methodology uses a TRM approach to visualize patent allocations and its evolutions
Viscio et al. (2014)	Space exploration/Scenario planning	The methodology uses scenario analysis, followed by a technology analysis from the database and a technology mapping, using TRM
Vishnevskiy et al. (2016)	Carbon fiber design	Integrated roadmap approach: The framework combines technology push and market pull TRMs using a cross-impact analysis
Authors	Context or application	Comments on the model
Weissenberger-Eibl and Speith (2008)	Disruptive technologies	Within a six steps approach, the information analysis, strategic anticipation, and decision-making are made, using database analysis and expert judgement
Yuan et al. (2012)	NPD/Scenario planning	TRM combined with scenario planning and patent analysis
Zhang et al. (2016)	Solar cell	TRM for competitive technical intelligence: the method is developed using qualitative and quantitative approaches, considering also STI factors
Zheng and Huang (2007)	Membrane structure	The TRM approach uses Delphi and analysis of experts with AHP

5. Conclusions

A relevant portfolio of articles related to the theme of TRM was obtained by searching the ISI Web of Science database. This article portfolio contributes to the extent that it allows the researcher to check articles of good reputation, as they are cited in many other articles that research the topic. The bibliometrics applied on this study and the content review of the papers have resulted in an additional research contribution on TRM field.

Since 2002, TRM, focusing in its alignment with models, has been generating interest in the literature during the years. Authors from England, South Korea and USA are predominant on the publications, which has also a high concentration of studies coming from research related to Seoul National University, in South Korea, and to the Centre for Technology Management at the Department of Engineering at the University of Cambridge, in England, led by Professor Robert Phaal, who has been the most active researcher when it comes to the search of TRM of this study.

Two sources can be taken as the most important when related to TRM studies content as they concentrate more than half of the publications of the search: the Journal of Technological Forecasting and Social Change and the Portland International Conference on Management of Engineering and Technology.

A content analysis of the main articles helped to guide future research and showed what has already been obtained by the authors in these articles. The evaluation of the keywords allowed an initial view of the link between words and how they are connected in portfolio of articles focused on the theme of strategy-aligned TRM, based on models. The words related to models inserted in the research allowed for the increased demonstration of a portfolio focused on articles that somehow seek or propose TRM models aligned with strategy and for the investigation of how these models are proposed and can improve performance in TRM. The systematized search approach is also noteworthy to identify TRM models created for specific applications and, by commenting on the models, can help research to define a suitable model, or one or more models to start with, when a new TRM is to be created.

The five articles citation clusters resulted in the bibliometric and content analysis of Chapter 4 and can help experts to direct studies on the TRM subject of each cluster, by allowing them to follow the connection between the research and define their interest points for further applications. The articles' citation analysis also plays an important role in allowing the researcher to understand the citation trend of the main articles and consequently its importance in the literature.

Authors' co-citation clusters, in turn, allowed for deeper analysis of authors who are cited together in the same article, bringing information to the researcher in what would be the search affinities of relevant authors in the subject. The analysis of clusters of authors also indicated areas of future within well-reputed articles by the authors previously mentioned. The clusters grouping these authors, named Roadmapping, Innovation and Implementation, are effective sources for each theme.

The TRM models applied in several cases were shown and described with the objective of showing the researcher the different aspects of the application of TRM in the several published studies, helping to direct practical application as well as future research

This study could serve as a basis for TRM research information aligned with strategies, as well as a source of references in the article portfolio for existing TRM models. As a limitation, the use of only one database of scientific publications stands out. To overcome this limitation, new research using other databases could contribute and enrich this study.

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