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Technology Roadmaps - From Design to Implementation

BIANCA ANDRADE DE CAMPOS
FUNDAÇÃO UNIVERSIDADE FEDERAL DO ABC (UFABC)
b.andradecp@gmail.com

LEANDRO RODRIGUES GONÇALVES
UNIVERSIDADE DE SÃO PAULO (USP)
lrgonc@usp.br

TECHNOLOGY ROADMAPS – FROM DESIGN TO IMPLEMENTATION

1. Introduction

Innovation, as a concept, is still under construction. As product systems become more complex, the new materials and technology become more sophisticated, but with the lingering world crisis, the resources become more and more limited. Among the challenges to continue providing improvements even with fewer resources, the activities of managing science, technology and innovation emerge (ACOSTA; ACOSTA; ESPINOZA, 2016; BIN; SALLES-FILHOA, 2012; PETRICK; ECHOLS, 2004).

Aligned to Competitive Intelligence and Technology Intelligence, the Technology Roadmaps (TRM) is gaining popularity and being adopted by companies, governments and other organizations, as a resource for managing the future of technology, driving innovation, providing a common vision between technologies, evolving/developing markets and products, reflecting an evolutionary organization of technology. In addition, the impact of changes in these concepts are assessed with expert judgment in an analytical way, in terms of potential threats and opportunities (PHAAL, 2004; RINNE, 2004).

2. Research Problem and Objectives

The objective is to study the Technology Roadmaps concepts, from design to implementation. Subsequently, by the analysis of a successful example of Technology Roadmap (NASA), possibilities and advantages of this important resource in Technology Intelligence are explored.

3. Literature Review

3.1. Technology Intelligence and Innovation

The last five decades of history have witnessed major technological changes and innovations that have fueled global trade and the evolution of international firms (ANDERSSON et al., 2015). Based on Competitive Intelligence (CI) concepts, the Technology Intelligence (TI) emerged aligned to these changes, to identify technology opportunities and help companies to be in the frontier of their innovation, avoiding surprises by the technical advances of competitors and defining steps to achieve stated outcomes and goals (PRESCOTT; MILLER, 2002).

In a summary definition, Competitive Intelligence is a dynamic process, which involves the gathering, analyzing and communicating of relevant information to assist in strategic decision-making. Porter (1980) demonstrated that the "competitive" intelligence concept implies the true purpose of intelligence, which is to gain strategic advantage. In the course of time, studies started to include the competitor intelligence as well as intelligence collected on customers, suppliers, environments, potential business relationships and technologies (DISHMAN; CALOF, 2008).

Considering technologies as a part of competitive intelligence is very interesting and helpful. The technology here is not only related with science and engineering ('hard' technology), but also involves the processes that enable its effective application – new product development and innovation projects – working together to support progress and achieve better outcomes and goals, in accordance with the company's objectives (PHAAL, 2004).

The innovation concepts are directly related to Technology Intelligence. Recently, ahead of the serious challenges faced by the industries due to the lingering global crisis, innovation has become an inevitable term in business strategy, in order to exploit ideas that turn into reproducible scale goods, when sold or implemented intelligently, to solve problems and generate value, providing improvements even when the resources are limited (ACOSTA; ACOSTA; ESPINOZA, 2016).

There are many innovation definitions, cited by different authors since this concept started to appear. OCDE (2005), for example, presented innovation as the introduction of something new or of a significantly improved product/process, a new marketing/organizational method, in the internal practices of a company, the organization of the workplace and external relationships (OCDE (ORGANIZATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT), 2005).

Innovation depends crucially on organizations ability to absorb external knowledge, combine it with their own proprietorial knowledge and develop new market offerings. To achieve this level, the strategic challenge is how companies can best organize the sourcing, codification and exploitation of the internal and external knowledge and informational resources, in order to maximize and sustain innovation, positioning itself strategically, knowing their goals and defining time frames to achieve them (LOVE; ROPER; VAHTER, 2014).

When the innovation department in a technology company starts developing the introduction of new products/processes and correlating this to new marketing/organizational methods, some questions can arise: *What is possible with our technology? Which technologies are out there for our molecules? What technology is valuable and needed by the organization? Which technologies fit with our organization?* These and other questions can be answered and enlightened applying the Technology Intelligence, with planned and strategic actions, supported by the development of Technology Roadmaps (ACOSTA; ACOSTA; ESPINOZA, 2016; VEUGELERS; BURY; VIAENE, 2010).

3.2. The Technology Roadmap Concept

A Technology Roadmap (TRM) is a strategic plan that describes the steps an organization needs to take to achieve stated outcomes and goals. It clearly outlines links among tasks and priorities for action in the near, medium and long term, providing a time-directed representation of relationships between technologies and products, linking technology to business needs (INTERNATIONAL ENERGY AGENCY - USA, 2014; OZAKI; DE VASCONCELLOS; BENGTSSON, 2015; RINNE, 2004).

Authors have been studying the TRM concepts since first appearances of this strategy, presented by Robert Galvin, the CEO of Motorola in the late 1970s and early 1980s. Other approaches used by organizations are closely related to technology roadmapping, such as forecasting, foresight, scenario planning, and backcasting. The particular feature of the technology roadmapping, and also its benefit, is the use of a time-based structure framework to develop, represent and communicate strategic plans, in order to provide the coevolution and development of technology, products and markets (PHAAL, 2004).

The first Technology Roadmap designed by Motorola emerged from the necessity to evaluate dangers and risks related to their processes and technologies, which were becoming much more complex over the years, to encourage business managers to give proper attention to their technological future, as well as to provide them a vehicle with which to organize their forecasting process. The emphasis of their first Technologies Roadmaps were (WILLYARD; MCCLEES, 1987):

- An objective evaluation of Motorola's capabilities in the technologies;
- A comparison of Motorola's capabilities and that of its competitors, today, and in the future;
- A forecast of the technologies progress.

These analyses provided a clear visualization of opportunities and threats, since showed the potentials and limits of the technologies.

The roadmapping process may vary from company to company, but it usually involves the analysis and linkage of three commonly present aspects already cited: technology, products and markets. The relations between these three concepts compose a generic technology roadmap (Figure 1) (OZAKI; DE VASCONCELLOS; BENGTSSON, 2015; RINNE, 2004).

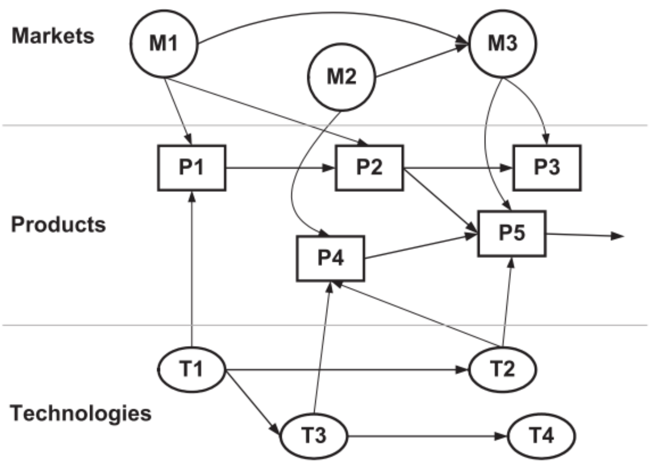

Figure 1. Generic Technology Roadmap (RINNE, 2004).

Ozaki et al. (2015) organized the main ideas of these concepts, as follows (OZAKI; DE VASCONCELLOS; BENGTSSON, 2015):

- Technologies Analysis: the most important part of product-technology roadmaps, usually very dense in information. The aim of this step is to analyze the evolution of the technologies used by the company – and which may replace them;
- Product Analysis: analysis of market needs, what competing products could be developed in order to achieve this, evolution of enterprise products;
- Market Analysis: definition of market segments that the company intends to achieve, competitor analysis, strengths and weaknesses analysis;

It is important to highlight that before the analyses of this concept start, a lot of research must be done. The company resources – capital investments/finance, supply chain, staff/skills – and the R&D programs/projects, have to be studied, in order to support balancing between the expectation and what can really be achieved (LEE, 2013).

An effective roadmapping process maximizes the participants’ engagement in creating the plan, thereby building consensus and increasing the likelihood that those involved will implement on the roadmap priorities. If some information is not available at the outset of the roadmap process, data collection and analyses should be developed as one of the initial roadmap activities and top priorities. It is crucial to set a vision, which will persist in all the future scenarios analyses and objectives identification (INTERNATIONAL ENERGY AGENCY - USA, 2014).

In summary, a TRM is a dynamic set of technical, policy, legal, financial, market and organizational requirements, identified by all stakeholders involved in its development. The effort is part of the Technology Intelligence strategy and takes in consideration how different aspects of internal and external environments will interact and influence the product portfolio and innovation choices. It shall lead to improved and enhanced sharing and collaboration of all related technology-specific RDD&D (Research, Development, Demonstration and Deployment) information among participants (INTERNATIONAL ENERGY AGENCY - USA, 2014; PETRICK, 2008). The goal is to accelerate the overall RDD&D process, to deliver an earlier update of the specific technology into the marketplace, identifying gaps, overlaps and opportunities, in order to facilitate communication and decision-making. Roadmapping enables space to different areas of the company to have conversations about possibilities and actions, creating a common view of the opportunity space and a common understanding of the best path forward (INTERNATIONAL ENERGY AGENCY - USA, 2014; PETRICK, 2008).

Other vision provided by TRM embraces the relation between new product development and innovation. New product development decisions that do not take into consideration the dynamics of technology evolution may result in investments that are unsustainable. Firms may see the new product options in the short-term as more profitable, but these investments lack long-term potential. Thus, the company must reinvest in subsequent technologies to remain viable. For this analysis, it is very important to consider the technology life cycles (S-curves), which are tied to improvements in performance resulted from R&D over time (Figure 2) (PETRICK; ECHOLS, 2004).

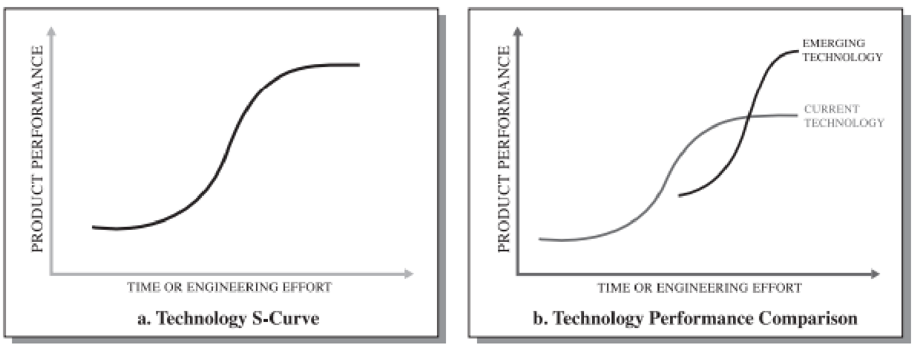

Figure 2. Technology S-curves help define performance over time and enable comparison of competing technology performance (PETRICK; ECHOLS, 2004).

Since the technology life cycles and related products are rapidly shortening, to support the TRM, a new concept of map is arising, the patent roadmap. Patents have been considered as an outcome indicator in R&D activities, as well as a vital element for analyzing technology, because it contains important technological and commercial information. The patent roadmap intends to analyze and plan patents to achieve technology planned on the TRM and can provide several candidate fields for research and development to create new technology derived from a pre-developed technology, saving double efforts and resources (JEONG; YOON, 2015).

3.3. Technology Roadmap – a Living Process

Roadmapping involves creating, implementing, monitoring and updating. The process is even more important than resulting documents, because it engages and aligns diverse areas in a common course of action, sometimes for the first time. In order to achieve a successful result, some key elements should be considered in the process logic (Figure 3) (INTERNATIONAL ENERGY AGENCY - USA, 2014).

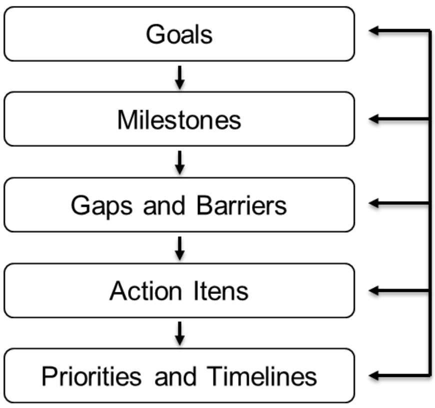

Figure 3. Key-elements in a successful roadmap (adapted from IEA, 2014).

The presence of these elements will provide a clear statement of the desired outcome followed by a specific pathway for reaching it. Their main aspects are shown in Table 1:

Table 1. Description of key-elements of a successful roadmap.

Key-element	*Definition*	*Objective*	*Example*
Goals	Clear and concise set of targets, quantified goals	If achieved, results in the desired outcome	“Improve the number of deposited patents by 25% in five years”
Milestones	Performance targets, pegged to specific dates	Achieving the goals	“Improve the number of deposited patents by 10% per year during the next five years, without slowing new products release”
Gaps and Barriers	List of potential gaps or other barriers to achieving the goals and milestones	Have consciousness about the gaps and discuss actions to overcome them	Gaps in knowledge, technology limitations, market structural barriers, regulatory limitations, public acceptance

(continuation)

Key-element	*Definition*	*Objective*	*Example*
Action Itens	Actions to phase out any gaps or barriers that stand in the way of achieving goals	To overcome gaps and barriers	Technology development and deployment, development of regulations and standards, policy formulation
Priorities and Timelines	Most important actions that need to be taken and the time frames for them	Achieving the goals	"Start a new technology project in 3 years".

Source: IEA, 2014.

On average, the development process of a roadmap takes 6 to 18 months. The process includes two types of activities (expert judgment and consensus, and data analysis – supported by landscape and foresights reports) and is composed of four phases (planning and preparation, visioning, roadmap development and roadmap implementation/revision). After the roadmapping process is completed, implementation and updating (using triggers and scenarios) ensure the complete achievement of the goals and vision, and can persist for 5 years, until the launch of a new roadmap (Figure 4) (INTERNATIONAL ENERGY AGENCY - USA, 2014; PETRICK, 2008).

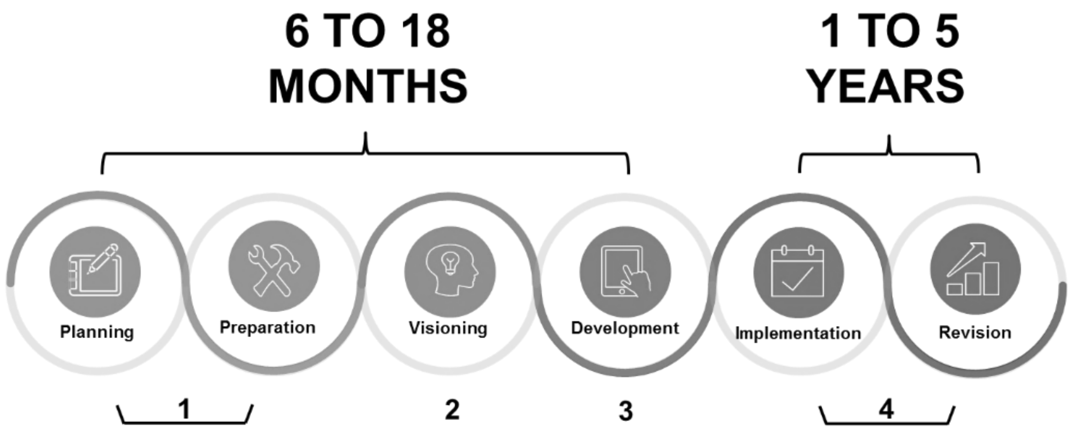

Figure 4. The roadmap development process.

At phase 4 (roadmap implementation, monitoring and revision), expert workshops have to be conducted, in order to reassess priorities and timelines as progress and new trends emerge. For this phase, data and analyses (indicators and modelling tools) are important to support monitor progress in implementing roadmap (INTERNATIONAL ENERGY AGENCY - USA, 2014).

It is fundamental to think about scenarios in which the roadmap developed is tangible. Then, analyze the key elements that are driving these assumptions. Some triggers should follow all the process of development and implementation. Here, triggers are the data elements that will be used to track the roadmap over time – they must have a tipping point – when reality begins to approach or exceed these tipping points, the roadmap must be reconsidered. This is one of the reasons to justify a roadmap committee with stakeholders who are most appropriate to conduct the process and to monitor the assumptions. The challenge is to empower these experts with knowledge about organizational goals and roadmap assumptions so that they can glean key changes from their respective environments, at the revision phase (Figure 5) (PETRICK, 2008).

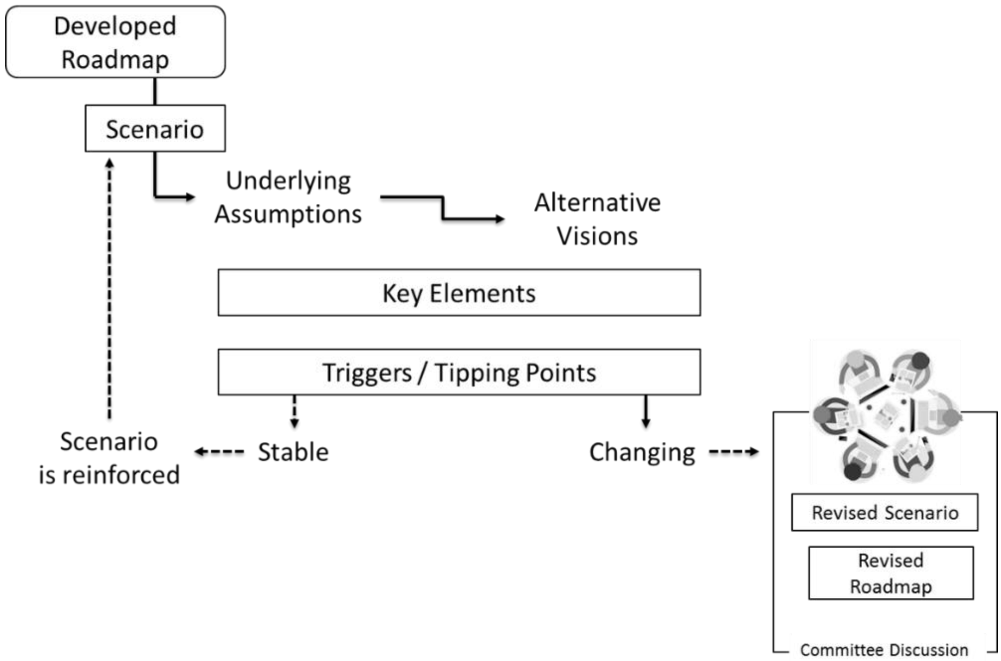

Figure 5. The implementation and revision phases include analyses to linking roadmapping to scenarios – developing a monitoring and updating strategy based on key drivers, triggers and tipping points (adapted from Petrick, 2008).

4. Methodology

Based on a careful literature review of the Technology Roadmaps concepts, we used secondary sources to establish analyses since the appearance of the first examples and articles published, with improvements and learnings provided as the tool was gaining popularity.

In order to make a connection between theory and practice, we used the Case Study approach. The Case Study approach provides a deep diving into the subject, to answer the research questions and objectives by a mix of qualitative and quantitative evidence. The essence of a Case Study, the central tendency among all types of this approach, is that it tries to illuminate a decision or a set of decisions; why they were taken; how they were implemented; and what results were achieved (EISENHARDT, 1989; SCHRAMM, 1971; YIN, 2015).

We used the holistic design, where just one case was selected, from NASA, an independent agency of the USA government, which develops state-of-the-art technologies and started to implement the TRM concepts successfully in the last ten years. The purpose of this methodology approach is to illustrate certain literature topics within a practical evolution and investigates the TRM concepts within its real-life context (YIN, 2015).

5. Case Study and Discussion – NASA Technology Roadmaps

The National Aeronautics and Space Administration (NASA), is an independent agency of the USA federal government, with almost 60 years of existence (1958). Responsible for aeronautics and aerospace research, as well as the civilian space program, the NASA's vision is to reach for new heights and to reveal the unknown for the benefit of humankind. Since their beginning, thousands of people have been working around the world (and off of it), to answer some basic questions (for example, *what is out there in space?*). NASA has been developing and using state-of-the-art technologies, to conduct its works in four principal organizations, called mission directorates – Aeronautics, Human Exploration and Operations, Science and Space Technology ("What does NASA do?", 2017)

The relation between NASA and technology is intrinsic. The agency has 7339 deposited patents (according to research done using the source software Derwent Innovations Index®), not just in aeronautics and human exploration subjects, but also in Materials and Coatings; Health, Medicine and Biotechnology; Environment; Electrical/Electronics; Communications; Power Generation and Storage, among others. In a list of organizations by number of granted USA patents in 2016, NASA comes in at #292, with 115 patents. The highest ranked governmental organization was the USA Navy, in #112, with 336 patents (IPO, 2017).

NASA published its first Technology Roadmaps in 2010. The collection was a set of 14 roadmaps to guide the development of space technologies under the leadership of the NASA Office of the Chief Technologist (OCT). The OCT was created to conduct strategy and leadership in order to integrate NASA's technology development and open innovation activities (partnerships), aligning the agency's technology investments to meet mission requirements while filing gaps, anticipating future needs, and minimizing duplication of effort (AMBROSE et al., 2015; CUTTS, 2016; STEERING COMMITTE FOR NASA TECHNOLOGY ROADMAPS, 2012).

There are two divisions at the OCT, named Strategic Technology Innovation and NASA's iTech Initiative. This last one is a yearlong effort to find innovative ideas that address challenges and will fill gaps in five critical areas identified by NASA as having a potential impact on future exploration, which are: autonomy; big data – data mining and machine learning; medical systems and operations; radiation protection and mitigation; x-factor innovations ("Office of the Chief Technologist", 2017).

The intent is to update the roadmaps every five years (a new version was published in 2015), to reflect changes in NASA's strategic direction. These roadmaps establish time frames and interdependencies of advanced space technology research and development over the next 5 to 30 years for pre-defined technology areas (TAs).

When the first TRM was being developed, four main objectives were established (STEERING COMMITTE FOR NASA TECHNOLOGY ROADMAPS, 2012):

- Establish criteria to enable priorization of technologies within each and among all of the technology areas which the TRM should satisfy;
- Consider technologies that address the needs of NASA's core technologies – named adjacent technologies;

- Integrate the outputs to identify key elements and issues and to summarize findings and recommendations;
- Select the highest-priority technologies from all 14 roadmaps.

The first TRM committee identified three descriptive factors that helped characterize each technology (STEERING COMMITTE FOR NASA TECHNOLOGY ROADMAPS, 2012):

1. Technology Readiness Level (TRL): describes state of advancement of the technology using a scale;
2. Tipping Point: used to determine if the technology was at a state such that a relatively small additional effort (compared to that which advanced the technology to its current state) could produce a significant advance in technology readiness that would justify increasing the priority associated whit this technology;
3. NASA Capabilities: to capture how NASA research in this technology aligns with expertise, capabilities and facilities available. It also assessed how much value NASA research in this technology would add to ongoing research by other organizations and foments – partnerships.

For each evaluated criterion, a set of four grades or bins were established – in order to qualify and classify the technologies.

After launching the 2010 TRM, meetings to review and approve the evaluation criteria and study process started, including the broad community, who was also solicited from a public website where individuals provided sets of comments on the draft roadmaps in terms of criteria (benefit, risk and reasonableness and alignment with NASA and national goals) (STEERING COMMITTE FOR NASA TECHNOLOGY ROADMAPS, 2012).

In 2014, a new TRM development team (42 members) was formed and in the spring of 2015, the new roadmaps were released to the public. The NASA Technology Roadmap development process and the 15 Technology Areas (TA) (addition of a new TA – Aeronautics) from the 2015 NASA TRM, are shown at Table 2 and Figure 6, as follows:

Table 2. Development Process and TRM & Priorization Topics.

Development Process	Technology Roadmap & Priorization
1. Mission Class;	10. Potential Technologies / Paths;
2. Design Reference Missions;	11. Current Investments;
3. Function;	12. Unmet Needs (Investment Gaps);
4. Capability;	13. Stakeholder Priorities / Possible Partnerships;
5. Parameter;	14. NASA Priorities.
6. Capability Performance Global;	
7. State of Art (SOA);	
8. Performance Gap;	
9. Technical Challenges.	

Source: IEA, 2014.

Figure 6. 2015 NASA Technology Roadmaps – Technology Areas (TA) ("Office of the Chief Technologist", 2017).

In order to provide a more complete TRM, NASA has identified a set of "cross cutting topics" (technology topics that cross multiple technology areas) to ensure a brief description of what is and how it maps into the main taxonomy. They are: Autonomous Systems and Artificial Intelligence; Avionics; Extra Vehicular Activity; Information Technology; In-situ Resource Utilization; Orbital Debris; Radiation; Space Weather; Sensors and Thermal Protection Systems. Improvements and discovery on these cross cutting topics sustain the development of the higher priority technologies. (AMBROSE et al., 2015; CUTTS, 2016).

In the 2015 NASA TRM, the final section "Technology Candidate Snapshots" was included, providing more complete information about each technology and highlighting specific crosscutting technologies, in order to offer an expanded description of specific performance goals, challenges and lists each Technology Candidate Snapshot number in the roadmap that corresponds to a crosscutting technology. (AMBROSE et al., 2015; CUTTS, 2016).

For each mission, the technology candidate is designated as enabling (a pull technology) or enhancing (a push technology). The enabling technologies are related with their missions at the Technology Candidate Snapshot, which includes the launch date (if determined), the technology needed date, and the estimated time to mature the technology. These dates prediction is provided by the section "Enabling Technology Candidates Mapped to the Technology Need Date", that shows in a dynamic way, the time frames between the development start date and the launch date. (AMBROSE et al., 2015; CUTTS, 2016). An example of a Technology Candidate Snapshot for the Nanotechnology TA is showed below (Figure 7).

10.1 Engineered Materials and Structures
10.1.1 Lightweight Structures
10.1.1.4 Low Permeability Nanocomposites

TECHNOLOGY

Technology Description: Provides lighter weight alternatives to metal liners in cryogenic propellant tanks and composite overwrap pressure vessels to reduce propellant loss.

Technology Challenge: Challenges include developing scalable manufacturing methods and techniques needed to bond film to composite tank and long-term durability under static and cyclic cryogenic propellant loading.

Technology State of the Art: Clay/polymer nanocomposites. Cellulose nanocomposite.

Parameter, Value:	TRL
Clay/epoxy nanocomposite films with 1,000 lower permeability than neat epoxy. Films made from cellulosic nanofibrils with low oxygen permeability.	4

Technology Performance Goal: Low permeability and good ductility over a wide temperature range.

Parameter, Value:	TRL
Permeabilty, toughness.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ultralightweight structural component.

Capability Description: Provides lightweight, structurally durable material for cryogenic tanks.

Capability State of the Art: Metallic liners.

Parameter, Value:
Gas permeability.

Capability Performance Goal: Improved adhesion to composite cryotank surface.

Parameter, Value:
Permeability, toughness, adhesion.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	8 years

Figure 7. Technology Candidate Snapshot for Low Permeability Nanocomposites ("Office of the Chief Technologist", 2017).

The NASA's TRM are a foundational element of the Strategic Technology Investment Plan (STIP) and are analyzed by the NASA Technology Executive Council (NTEC) in order to make decisions related to technology policy, priorization and strategic investments. Together, the STIP and TechPort (a software to support data source and decision) provide NASA the ability to manage the technology portfolio in an innovative way. After the developments, the patent portfolio, licenses and software catalog are available to public by TechFinder (https://technology.nasa.gov/), it is possible to elucidate this technology development cycle at Figure 8:

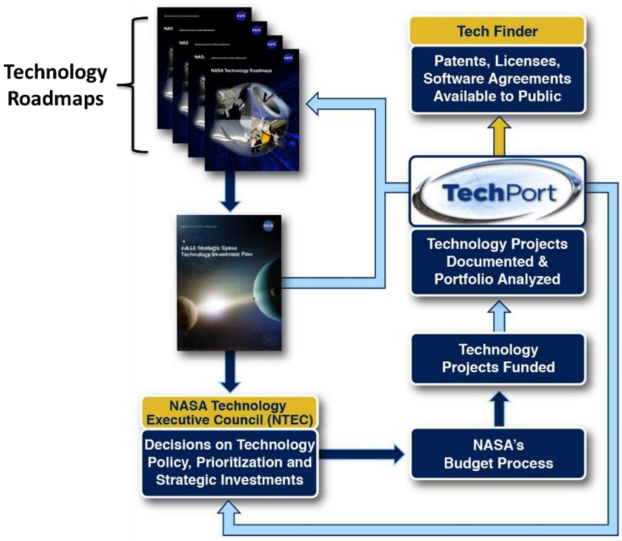

Figure 8. NASA's Technology Development Cycle and Strategy ("Office of the Chief Technologist", 2017).

6. Conclusion

The roadmapping process is a great example about how innovation concepts are changing the organizational perspective. As an important Technology Intelligence resource, these solid studies and predictions emerges in a scenario where the business environment is in constantly movement and the industries are facing serious challenges to transform limited resources in improvements.

The decision-making to achieve goals and outcomes need to involve planned and strategic initiatives, in order to enable the highest impact tasks from the simplest to the mainstay technology. The priorization does not happen only for core technologies, and the priorities order is also determinant to encourage the company to envision what might be next in line, for achieving better results and making right choices.

As showed on the case study, NASA is a leading example of a technology agency that implemented the Technology Roadmaps on their strategy. Through a common vision, warranted by the NASA Office of the Chief Technologist, the roadmaps are correctly designed, linking projects by a logical structure and achieving goals by the definition of desired pathways and time frames for deployment.

The NASA's Technology Roadmaps analysis showed many innovative sections which should be taken as examples of how to introduce this tool successfully. The Technology Candidate Snapshot is on a noticeable spot on these examples, as it summarizes the roadmaps information and provides a strong relation between all the actions and pathways to be followed and monitored.

Far more than a graphical representation of the technologies, products and market evolution, the roadmapping process itself is of great value, since enables learning and greater integration among diverse company areas through interactive and multidisciplinary meetings and workshops.

After the roadmap development process, the integrated areas of the technology companies can response many questions that were not clear before. It is possible to have a vision of all the possibilities offered by the own technologies, to realize which molecules/technologies can be applied in other segments/markets and to identify the necessity of new capabilities development (from novel cutting-edge technologies). The actions clearly defined, generate more value and enable the understanding of gaps and limitations that should be overcome in time to provide the achieving of defined milestones and goals.

Aligned with innovation concepts, providing a smart decision-making and collaboration between different areas of the company, the technology roadmapping is a tendency to transforming business, driving growth and enhancing competitiveness by the technology development strategy.

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