MODEL-BASED TECHNOLOGY ROADMAPPING: POTENTIAL AND CHALLENGES AHEAD

Raffaele Gradini

Georgia Institute of Technology
North Ave NW
Atlanta GA 30332 USA
rgradini3@gatech.edu

Sandro Salgueiro, Jyotsna Budideti

Airbus
18 Rue Marius Tercé
31300 Toulouse, France
sandro.salgueiro@airbus.com

Alessandro Golkar

Skolkovo Institute of Science and Technology
Bolshoy Boulevard 30
121205 Moscow, Russian Federation
a.golkar@skoltech.ru

ABSTRACT

This paper explores the application of Model-Based Systems Engineering principles to technology planning and roadmapping. Technology roadmapping is a methodology that is widely used in industry to plan and explore interdependencies between research and development, products, markets, and other strategic factors. This paper describes model-based technology roadmaps as a quantitative implementation of the roadmapping methodology in order to encode, explore, and generate insights from structured knowledge and expert elicitation. The paper shows the application of model-based technology roadmapping on a publicly available NASA roadmap, discussing strengths and challenges of the proposed approach. The paper provides an analysis of model-based approaches to technology roadmapping, and provides recommendations on the evaluation of complexity in implementing model-based roadmapping, identifying avenues for further development of the approach.

Keywords: technology roadmapping, technology evolution, model based systems engineering

1 INTRODUCTION

Technology roadmapping is a process in technology planning to explore and communicate interdependencies between markets, technologies, and products, over time (Phaal, Farrukh, and Probert 2004). Roadmapping is widely employed in technology organizations to support decision making in different contexts, although the formalization of roadmapping techniques in the literature is rather a new field field of investigation. Roadmaps are developed to support research and development, product development, business strategy, and so on. Kostoff and Schaller distinguish between expert-based and computer-based approaches to roadmapping (Kostoff and Schaller 2001). In expert-based approaches, expert teams are convened to define roadmaps on an iterative basis. Expert-based approaches are usually qualitative and leverage on the experience of subject matter experts and leadership teams inside the organization. In computer based-approaches, information databases are compiled and then analyzed using computational approaches (Kostoff and Schaller 2001). Computer-based approaches encode knowledge that is present in the organization, and allow for systematic analysis that is used in support of decision-making processes. In many cases, expert-based and computer-based approaches are blended together into hybrid approaches that allow reaping the benefits of both while mitigating their respective limitations. One could think of model-based technology roadmaps as an evolution of roadmapping practice where knowledge is encoded and explored using models (Knoll, Golkar, and Weck 2018).

In this paper we explore the case of model-based technology roadmapping as an application of Model-Based Systems Engineering (MBSE) principles to the understanding of technology evolution for technology research and development planning purposes. We consider technology roadmaps as models including a taxonomy, a data structure, and encoded knowledge. Using the 2015 NASA technology roadmaps (Council 2012) available in the public domain as an example of document-based roadmaps, we identify the opportunities enabled by model-based roadmaps and discuss analytics enabled by computational analysis of roadmap models and data driven roadmapping process. Lastly, we identify any challenges in the practical application of model-based technology roadmaps by looking at the *TA1 Launch Propulsion Systems* roadmap (Council 2012) as a case study and addressing potential issues in the implementation of model-based approaches in industrial practice.

The remainder of the paper is structured as follows. Section 2 compares document-based technology roadmaps to model-based technology roadmaps, identifying advantages and challenges of both approaches. Section 3 provides a proof of concept of model-based technology roadmaps based on a NASA technology roadmap example available in the public domain. Section 4 discusses challenges in the introduction of model-based technology roadmapping in engineering management practice. Lastly, section 5 draws conclusions from the papers and identifies avenues of future work.

2 DOCUMENT-BASED VERSUS MODEL-BASED TECHNOLOGY ROADMAPPING

For decades companies have looked to technology roadmapping to plan their long term strategic technology investments (Garcia and Bray 1997), and to rationalize smaller projects within the context of structured technology investment portfolios. The earliest reference of technology roadmaps in the literature is the Product Technology Roadmap of Motorola, as a compilation of documents providing information on past, present and future of the product line of the company (Harring 1984). Roadmapping identifies and prioritizes technology investments. In large organizations, technology roadmapping aligns corporate departments towards synergetic, cross-divisional technology strategy goals for the organization. There is no single process for roadmapping and organizations either create one themselves or use known processes such as the T-Plan roadmapping process proposed by Phaal (Phaal, Farrukh, and Probert 2004).

Roadmapping activities are typically pursued through facilitated workshops, with experts contributing from different sides of the organization. For technology organizations, these include market strategy, product, and technology. Technology roadmaps are ultimately encoded into documents, such as presentations and reports. For instance, Figure 1 shows the generic roadmap template proposed by EIRMA (EIRMA 1997).

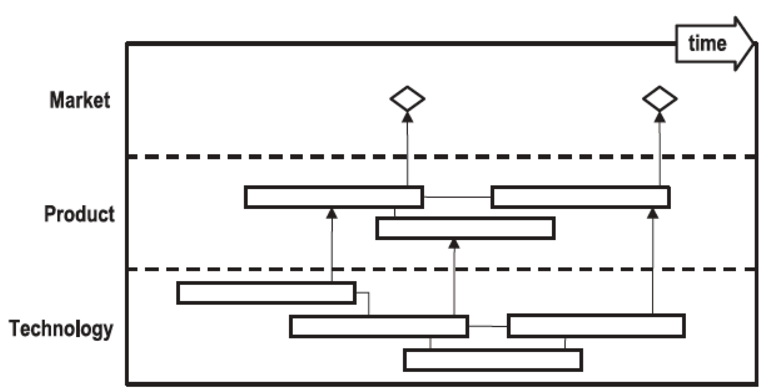

Figure 1: Generic technology roadmap template (EIRMA 1997).

The template is a graphical representation of a roadmap linking market, product, and technology processes together, enabling an overview of the context of technology development in the bigger picture. (Phaal, Farrukh, and Probert 2004) identifies eight different types of roadmap purposes and roadmap formats, respectively. All formats identified are document-centric. Academic review papers can be interpreted as another instance "*at-large*" of document-based "roadmaps," meant as surveys of the state of the art and outlooks of future developments. Regardless of their structure, all document-based technology roadmaps exhibit common limitations that are common to static data sources. For instance:

- They require manual rework and replanning over time as business conditions evolve, while uncertainties and ambiguities unfold over technology developments (Golkar and Crawley 2014);
- They are prone to inconsistencies due to the high number of interdependencies between technologies. Motta et al., for instance, report over 4,000 relationships between product and technology parameters in the technology roadmapping system of Pirelli (Motta et al. 2015);
- Human analysts are required to process a significant amount of data in parallel, in order to generate insights coming from the cross-correlation of the data in the roadmaps, while accounting for the dependencies between market, product, technologies, and external factors such as partners and competition;
- They do not allow immediate answers to transversal questions, such as assessing the number of projects impacting a given technology, or identifying potential future roadblocks in production or other phases of the lifecycle;
- They limit the amount of automation in the process as a human interface is required to manage, control and update the documentation;
- Given the static nature of the documents this approach is oriented towards a single point solution. This limits the amount of open options that the organization can explore during the development phase, reducing therefore the adaptability of the product in an evolving market (Kirby and Mavris 2001);
- They limit the connection with the industrial setup of the company, forcing, in case of a design mistake/inconsistency, either a re-work of the documentation or a search for a solution on the shop floor;

Model-based roadmaps, on the other hand, offer a dynamic approach to technology roadmapping. The first benefit they offer is the adaptability of the product through the development cycle to the market changing conditions, allowing the company to carry a product family rather than a single point solution (Freeman 2013). During the development of a product, model based roadmaps help in keeping the number of possible solutions broad enough to allow for the design of a family of products rather than a single point solution. Product family development has been one of the criticalities of the aerospace industry. In the past to amortize research and development costs of an aircraft while tapping new markets, an already existing single point solution product was stretched or shrunk to satisfy market requirements, while also downgrading performances. Model-based roadmaps allow for parametric exploration of all the life stages of the products, increasing the understanding of the evolution of the asset through its lifecycle. Having a dynamic roadmap allows organizations not only to test more easily different scenarios, but also to analyze in a faster and more precise way how different technologies will impact the product. This analysis could be also used to evaluate and quantify which upgrades are needed to tap new market with an already existing product, enabling the user to broad the scope of the roadmap as needed. A model-based roadmap can allow the design to be directly connected with non-engineering units as procurement or market forecasting, increasing common understanding of how each department of the company contributes to the overall final design of the product. The link to business and market forecast unit can be used to narrow the different design solutions depending on the evolution of the market in terms of customers distribution and needs.

Having a model behind the roadmap can also increase the connection with the industrial set up that has to manufacture and/or assemble the products, modelling how each components is going to be assembled ensuring therefore the presence of specific tools and the space for the worker to safely operate. This tighter collaboration allows for a better streamlining of the operation at manufacturing level, for example reducing the overall lead time on assembling operations (Suganthini Rekha, Periyasamy, and Nallusamy 2016). Reducing lead time is one of the key benefits that model based roadmapping provides, the shorted lead time allows for either a quicker reconfiguration of the product in case of market changes or for a deeper understanding of the product itself allowing a reduction in epistemic uncertainty coefficients. In order to assist and enhance the process of analysis, simulation and optimization of roadmaps, a computational representation of all elements of Technology Roadmapping becomes crucial. Thinking of a complex network of technology roadmapping, the roadmaps, stakeholders, projects, markets and their interdependencies, a model-based approach provides the required framework to effectively capture the entire roadmap system as a network-graph that facilitates computational analysis.

3 MODEL-BASED TECHNOLOGY ROADMAPPING APPROACH: USE CASE

In 2015, NASA released the latest version of their publicly available technology roadmaps. According to the agency, *"the 2015 NASA Technology Roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years (2015-2035)"* (NASA 2015). NASA has divided its technology roadmaps in 15 documents, with each covering a specific technology area. These documents are labeled TA1 through TA15, with TA standing for Technology Area. Examples of technology areas represented by these roadmaps are Launch Propulsion Systems, Habitation Systems, and Nanotechnology. Each of the 15 roadmap documents is a list of the many technology "blocks" that the agency seeks to develop in order to enable sought-after capabilities. In addition to listing these technology blocks, each roadmap document also provides a schedule of technology development, as illustrated in Figure 2.

Figure 2: Example of technology development schedule taken from the NASA TA1 roadmap.

In the example of Figure 2 above taken from TA1, a timeline is given along with three specific technologies (abbreviated by their IDs 1.6.1.1, 1.6.1.2, and 1.6.3.1), a date for when the technologies are needed to enable a new capability (2020), and finally the launch dates of actual missions that seek to make use of the newly developed capability (2023 and 2029). Each of the individual technologies, such as 1.6.1.1, are further detailed on separate pages that contain an overview of the technology, its Technology Readiness Level (TRL), and its desired future TRL.

1.1 Solid Rocket Propulsion Systems
1.1.6 Integrated Solid Motor Systems

1.1.6.1 Five-Segment Advanced Solid Rocket Booster

TECHNOLOGY

Technology Description: New five-segment booster option for SLS Block 1 derived from Shuttle four-segment solid rocket booster (SRB) that provides thrust increase to meet 70 mt payload requirement.

Technology Challenge: The liner and insulation.

Technology State of the Art: Currently under development through Space Launch System (SLS) Program.	**Technology Performance Goal:** Thrust increase needed to meet 70 mt payload requirement.
Parameter, Value: Sea level thrust: 3,300,000 lbf — **TRL** 7	**Parameter, Value:** Sea level thrust: 3,300,000 lbf — **TRL** 9

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

CAPABILITY

Needed Capability: Five-segment Advanced Solid Rocket Booster.

Capability Description: New five-segment booster option for SLS Block 1 derived from Shuttle four-segment SRB that provides thrust increase to meet 70 mt payload requirement.

Capability State of the Art: Shuttle reusable solid rocket motor (RSRM) at 12.2 foot diameter produced 2,800,000 lbf thrust at sea level.	**Capability Performance Goal:** Thrust increase needed to meet 70 mt payload requirement.
Parameter, Value: Sea level thrust: 2,800,000 lbf	**Parameter, Value:** Sea level thrust: 3,300,000 lbf

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
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	1 year

Figure 3: Overview of technology 1.1.6.1 from TA1 (image source: NASA).

In the overview page of the technology (Figure 3), one can see its actual name (in this case, Five-Segment Advanced Solid Rocket Booster), as well as a description. Also noteworthy is a stated TRL value for the technology (TRL 7 in this case), as well as the TRL level desired by the target date of 2022 (TRL 9). This document-based roadmap architecture developed by NASA is easy to interpret and provides a reasonable amount of clarity and direction to the research being conducted at the agency. It does not, however, attempt to apply model-based techniques in order to optimize R&T investments. For large commercial organizations attempting to simultaneously rationalize and optimize investments made in early technology development (i.e., R&T), a more complex approach relying on model-based roadmaps is needed. Let us then investigate the steps needed to transform a document-based roadmap, such as the NASA TA1 roadmap, into a model-based roadmap that can achieve these goals.

Besides a precise timeline of when certain capabilities are required for product development, a model-based roadmap requires an additional abstraction: technologies and capabilities must be linked through physical attributes. In a nutshell, we must develop a clear understanding of how technologies (e.g., five-segment solid rocket booster) affect capabilities (e.g., ability to launch heavier payloads using solid rocket boosters). In a model-based roadmap, these cause-and-effect relationships are described by Figures Of Merit (FOM) and technical models (i.e., transfer functions). By linking desired capabilities to target technologies by means of technical models, many of the main benefits of model-based roadmapping can be achieved:

- The impact of technology development on capabilities can be quantified. For example, in a model-based architecture, it is possible to consult the roadmap at any time in order to visualize the relationship between the thrust of a solid rocket booster (technology) and the maximum payload mass that can be achieved with this thrust (capability). The consequences of exceeding or failing to meet the target thrust can also be readily quantified.

- The model-based roadmap is self-contained and provides objective answers to stakeholder questions. While in a document-based roadmap the content of the roadmap can be challenged and modifications can take significant effort, stakeholders can become more active participants in the building of a model-based roadmap. If assumptions behind models are questioned by stakeholders, they can be made part of the process of identifying and agreeing on assumptions, and changes in results can be immediately quantified under the new assumptions.

In addition to a logical hierarchy of capabilities and technologies linked by technical models, a complete model-based roadmap architecture can also include a financial abstraction: technologies can be linked to individual R&T projects (these are the actual projects being funded in order to develop the technologies) through financial models that enable the organization to translate monetary investments into the expected technology performance improvements. In short, with the implementation of both the technical models and the financial models, a model-based roadmap architecture allows the organization to track not only how individual technologies are expected to affect capabilities (technical models), but also how the funding of specific R&T projects impacts the delivery of the capabilities (financial models).

As we discussed before, linking financial to technical models is the key to relate performances to money. In this specific use case we can see how every increment of the selected FOM (Sea Level Thrust) has a price attached to it, but given the governmental nature of NASA, this price now become an investment on: technology development for the country and on supporting the industrial ecosystem that will have to develop the product. As in many governmental program it is possible that for the roadmap to be carried by a consortium of companies with one main contractor who can guarantee the deliverables and the necessary economic liquidity. Sharing information among the partner of the consortium is a critical point, as wherever there are interfaces there is a higher probability of defects and mistake. Model-based roadmapping helps in solving this problem by smoothing the organizational boundaries intra-consortium. Looking again at this specific roadmap, it is expected that the booster will be manufactured in batches to support the missions of SLS throughout its entire life. The contract for the manufacturing might be given to a different consortium of companies with a different prime contractor, which means that a technology transfer has to happen from the first consortium to NASA to the second consortium. Having a model behind the roadmap ensures that all the assumptions (stated or implicit), codes, requirements and everything else approved by the customer (NASA) is passed to whoever will manufacture the boosters. During the life of SLS the model built for the roadmap can be used to optimize and increase the sustainability of the boosters from both the engineering and the economic points of view.

4 MODEL-BASED TECHNOLOGY ROADMAPS: IMPLEMENTATION CHALLENGES

4.1 Balancing value and complexity in model-based technology roadmapping

In the effort of technology roadmapping, the complexity of the desired roadmap system must be carefully considered ahead of its creation. Roadmap complexity and the effort required for roadmap creation and updating is likely to be increased by the inclusion of elements such as technical models, interdependencies between roadmaps, and financial valuations of research projects. However, despite increasing the complexity of the roadmapping task, these elements also have the potential of making the roadmapping activity richer and more meaningful. It is therefore important for organizations launching a new roadmapping effort to decide 1) what the expected output from the roadmapping activity is, and 2) how much time and resources the organization is willing to allocate to the effort. If launching a roadmap activity for the first time, an organization may be faced with unforeseen difficulties, as the consequences of roadmap complexity can be hard to estimate at first. In this regard, starting small and scaling the effort progressively should be considered a good practice. In order to rank roadmap complexity, we propose the technology roadmap complexity classification shown in Table 1.

Table 1: Proposed technology roadmap complexity classification.

Roadmap complexity	**Desired output**	**Description**
Low	Documents agreed upon by experts that describe the organization's plan and schedule for developing new technologies and capabilities at a high level.	The lowest complexity roadmaps are simple documents that describe the organization's plan to develop new technologies and capabilities within certain areas of research. Their main objective is to provide clarity and direction to all research within the organization. At this level of complexity, the roadmap likely does not describe specific research projects needed to reach the target. Its purpose is to simply be a guiding document that will add clarity to future decision-making.
Medium	Documents and models developed by experts that describe the organization's plan and schedule for developing new technologies and capabilities, including a demonstration of the positive impact of given technology improvements by means of technical models.	Medium complexity roadmaps usually have some sort of modeling included in the roadmap documents that enable the quantification of benefits derived from given technology improvements. In addition to providing clarity and direction to the organization's research activity, the roadmaps and models allow decision-makers to sequentially analyze different technology development scenarios by making use of the technical models.
High	Model-based roadmap architecture that includes both technical and financial models of technologies, plus documents that serve as supporting material.	High complexity roadmaps rely on the idea that decisions regarding what research projects should be funded in order to reach a certain target can be made systematically by relying on technical models and financial valuations of projects. By introducing both technical and financial models for every technology in the roadmap system, a fully model-based roadmap architecture strives for the optimization of the organization's investment in new technology development. Compared to low complexity roadmaps, high complexity roadmaps enable investment decisions that are much more data-driven. However, they require significantly more time and resources in order to be properly developed.

It is important to note that the complexity levels described above are relative to the size of the organization. Implementing a high complexity roadmap system in a small organization, for example, might be easier than implementing a medium complexity roadmap system at a large organization. It is therefore crucial for roadmap architects to seek to understand how roadmap complexity would scale in their own organizations.

4.2 Managing roadmap complexity through computational analysis

With increasing complexity, the roadmap system as a whole becomes increasingly challenging to use. Computational analysis becomes in assisting stakeholders and decision makers in extracting insight from a model-based roadmapping environment. A possible approach is to represent the roadmap system as a network-graph with nodes and edges (Boccaletti et al. 2006). In this approach, each node is any element in the roadmap system for example a roadmap, project, technology block, technology area, market area or strategic focus area. These nodes hold information defined during the model-based roadmapping process such as textual description, dependency links, target year, and investment made. The edges between the nodes represent the cause-effect relationships, all derived from the input from individual stakeholders involved in roadmapping process of each roadmap as a first step (Figure 4).

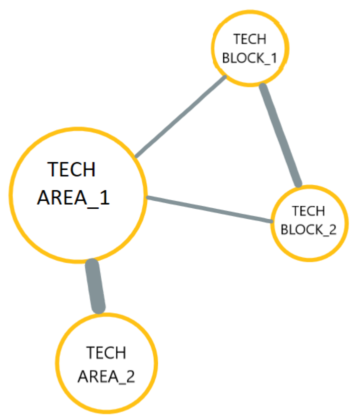

Figure 4: Representing roadmap system as a network graph.

The edges can be weighted based on the strength of the dependency driven by the technical models. Exploring this network graph of the complete roadmap system, one can already find interesting insights from this new global perspective and visual nature of network graphs. A very common topic in the study of complex networks is community detection. Communities are groups of nodes in our case roadmap elements which probably share common properties and/or play similar roles within the graph (Fortunato 2010). On performing this analysis on the roadmap system graph, the decision makers get key insights on how the roadmap elements are grouped and hence the nature of current technology strategy, if it is diverse, if it is too biased towards any group, or if there are any singleton technology block or project or if the strategy is not too diverse enough. These are some of the questions the decision makers can start asking as a result of this analysis.

In a very complex network of technology roadmaps, it is common to have duplication of effort or unidentified links within the structure as a consequence of complexity and multi-dimensional and hierarchical nature of real complex systems. And hence we propose the second step of computational representation : data driven roadmap system dependencies (Figure 5).

In this step, knowledge from textual descriptions and documentation on each roadmap element is augmented. A semantic analysis based algorithm is used to ascertain a measure of commonality between all types of roadmap system elements generating a knowledge-based graph.

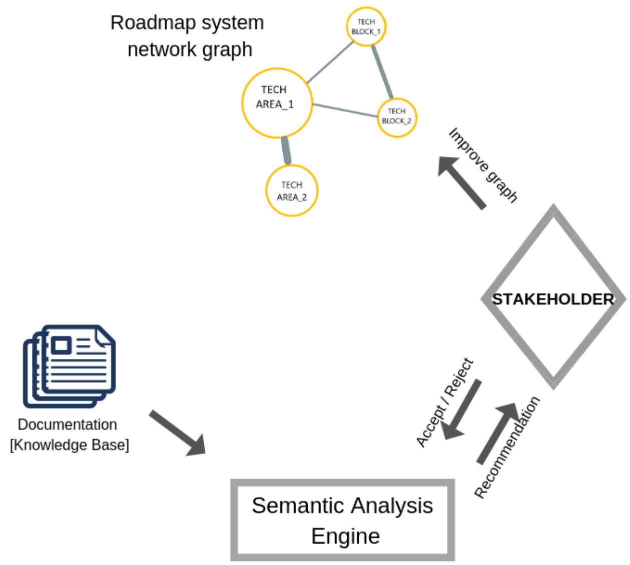

Figure 5: Data Driven approach: functional diagram.

Using semantic analysis we can automatically identify cross-functional dependencies between roadmaps. For example, coming back to the TA1 *Launch Propulsion Systems* Roadmap from NASA, we can identify actual and potential dependencies between structural and propulsion research in the development of a launch system. This allows stakeholders to focus their attention on validating or rejecting these suggestions which in turn will help the algorithm learn. This method assists decision-makers to visualize the global picture without losing the granularity when required and focus on decision making with continuous real time feedback on how any decision impacts the rest of the roadmap network. A computational approach to roadmaps allows to objectively identify cross-technology dependencies in research investments, as well as identifying gaps in research investment strategy when cross-analyzing with external sources of technology data (such as the technical literature). Roadmap elements to which this approach can be applied include, among other elements: projects, technologies, products, markets, and strategy. It allows to identify synergies between projects, identifying opportunities for improving the efficiency of the overall investment of the organization. The first challenge in computational analysis of technology roadmaps include the initial effort required to implement the system, including data gathering and organization. The second challenge is the learning curve required for users and decision-makers to extract insights from computational analysis, as well as to find the appropriate representations to provide useful synthesis of results for the management.

5 CONCLUSION

Model-based Systems Engineering can be effectively applied to the practice of technology roadmapping. Technology roadmaps can be analyzed, queried and interconnected using MBSE. In this paper we have shown the potential of model-based technology roadmapping to increase the value of research investments by organizing and identifying interdependencies between technology blocks, research projects, market assumptions, product strategy, and so on. A model-based approach to technology roadmapping can be implemented from either bottom-up or top-down views. In a bottom-up approach, one would start modeling a portfolio of existing projects and build up a set of roadmap models based on the interdependencies identified. In this case, the network analytics approach discussed in Section 4 provides a tool for fact-based clustering of projects into cross-functional roadmaps. In a top-down approach, modelers pre-define a set of roadmaps based on a technology block decomposition of the research portfolio (such as in the case of the NASA technology roadmaps). Technology blocks are then defined and linked to each other through technical and financial models. The roadmapping system created in this way can then be used to generate insights to inform planning of investments and to define projects. In this paper we have introduced some of the key ideas of model-based technology roadmapping. Much remains to be done in defining model-based technology roadmapping. We have proposed an initial classification of the complexity involved in the implementation of model-based roadmapping. Approaches to mitigate complexity include the development of an open-source set of technical models (that could be codified in standards) that could be used by research organizations and industry alike to build proprietary technology roadmaps. The challenge in standardization is the preservation of intellectual property and confidential information of the organization. Additional insights can be generated by an automated exploration and enrichment of the roadmaps, through the application of modern machine learning techniques in exploring the open literature and benchmarking with roadmap datasets to identify gaps and opportunities in technology development.

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AUTHOR BIOGRAPHIES

RAFFAELE GRADINI is an aerospace system engineer and PhD student at the Georgia Institute of Technology. He holds a Master's degree in Space Science and Technology from the Skolkovo Institute of Science and Technology. His research areas focus on system engineering for complex defense systems, with particular interest on mission architecting and technological gap analysis for preliminary design. He can alternatively be reached at gradini.r@gmail.com.

SANDRO SALGUEIRO is an aeronautical engineer at Airbus. He holds a Master's degree in Aeronautics and Astronautics from the Massachusetts Institute of Technology. His work focuses on the study of future air transportation concepts, including the study of aircraft design, air traffic management, airport infrastructure, and airline operations. Sandro is also a rated commercial pilot. He can alternatively be reached at sandrosr@mit.edu.

JYOTSNA BUDIDETI is a machine learning engineer at Airbus. She holds a Master's degree in Applied Mathematics from École Polytechnique. She is passionate about building intelligent autonomous systems to be deployed in the physical world. At her work she applies her expertise in Artificial Intelligence to develop next generation Aerospace products and systems. She can be reached at jyotsna.budideti@polytechnique.edu.

ALESSANDRO GOLKAR is an Associate Professor at the Skolkovo Institute of Science and Technology. He holds a Ph.D. in Aeronautics and Astronautics from the Massachusetts Institute of Technology. His research looks at new ways for looking at complex systems architecting problems, understanding the evolution of technology, and developing research and demonstrators of novel space mission concepts and spacecraft payload systems. His email address is a.golkar@skoltech.ru.