A framework for developing a Risk-Adaptive Innovation-based Technology Roadmap using TRIZ, Analytic Network Process, and Bayesian Network

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Abstract

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Ali Mohammadshahi

In recent decades, companies, industries, and even governments have been motivated by technological advances to improve alignment between their strategic objectives and technology management and innovation by applying flexible and structured methods. Technology roadmapping has been a well-accepted response to this need by organizations. Technology roadmapping is an important tool widely used within industries for collaborative technology planning. It is considered a flexible technique to support strategic and long-range planning and coordination for corporations or entire industries. The technology roadmapping (TRM) approach provides companies or industry sectors with a well-structured and often visual pathway for investigating the relationship between emerging and developing markets, products, and technologies. This technique can also benefit a turbulent business environment and protect companies from potential losses. Moreover, the flexibility and benefits of this technique have led to a rapidly increasing literature for TRM, and companies and industries have been adopting this technique increasingly.

Despite the deceptively simple format of technology roadmaps, there are significant challenges in their implementation and development as mainly the scope is generally broad and contains complex concepts and involves human interactions. Moreover, there is little practical support available for TRM, and the companies applying TRM typically need to re-invent the process and adapt it to their business situation. In addition, TRM does not cover the area of innovation when a required technology does not exist and needs to be developed. Therefore, they need to be equipped with technology development solutions and means to assess their risks.

This research proposes an innovation-based risk-adaptive TRM process for those companies that need to develop products and services for which the required technology is not yet existing. It presents an integration of the Theory of Inventive Problem Solving (TRIZ) and TRM throughout the roadmapping process as well as the Analytic Network Process (ANP) for final decision making between alternative technologies. The proposed method also uses a Bayesian Network Model to investigate risk propagation in the roadmap.

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TRM	Technology RoadMapping
QFD	Quality Function Deployment
TRIZ	Theory of Inventive Problem Solving
ANP	Analytic Network Process
AHP	Analytic Hierarchy Process
BN	Bayesian Network
VBN	Vectorized Bayesian Network

Chapter 1

Introduction

1.1. Motivation

In the era of technological advancement and globalization, companies are facing many emerging challenges. Products are getting more complicated and customized. The product life cycle is shortening, and the time to market is continually shrinking [1]. There is increased competition resulting in cutbacks. Such problems require companies to focus on and have a better understanding of their industry and market. It has become necessary for companies to understand the relationship between their technological capabilities and corporate objectives. Therefore, technology and innovation management have become more and more critical for companies as the center of the corporate decision-making process and a great help to deal with this increasingly competitive business environment [1] [2] [3]. Decisions not incorporating technological considerations for the development of innovations cannot be sustainable [4].

Since the rise of the Technology Roadmapping (TRM) method, six key process models have been proposed for developing technology roadmaps. Phaal et al. [5]introduced the Fast-start approach, which is based on multifunctional workshops. Their method is particularly suitable to support innovation and strategy at the product and business level [5]. Schuh et al. [6]introduced a technology-driven view. Their process starts with analyzing the evolutionary trajectory of a technical system. Following this approach, enterprises can systematically identify and evaluate technologies and align them with their business strategies in the early stages of market opportunities [7]. Geschka et al. adopted a market-driven view for developing an explorative technology roadmap [8]. Their method was mainly based on environmental scenarios, letting the enterprises cope with changing external influencing factors. Moehrle introduced a contrasting technology-driven TRM based on the Theory of Inventive Problem Solving (TRIZ) [9]. This method exploited opportunities inspired by technology and added a market-based view in the later stages. Kanama et al. introduced the integration of market- and technology-driven views [10]. For this purpose, they involved the Delphi process from the starting point of TRM. Moreover, Abe proposed a business-oriented model for normative TRM [11]. Instead of concentrating on a prognosis of the future, Abe focuses on a vision of what can and should be achieved in the future. Figure 1.1 illustrates the contributions positioned against different visions of the future. Exploratory process models tend to identify and develop further opportunities, while goal-oriented approaches can provide more details in strategic planning.

On the other hand, market-oriented process models help companies ensure appropriate technological capability is available, while technology-oriented approaches explore new exploitation opportunities [11]. In most of these models, the process focuses on a single vision, and the opposite vision's importance is neglected. It leads to a weak linkage between the market drivers and technology drivers. Also, regardless of the focus of the process model, the part that all these models are missing is the risk associated with the entire process considering today's rapidly changing and complex business and industry environment [12].

This research aims to develop an exploratory TRM process model that also considers the market drivers to make sure that required technology capabilities that are not yet developed will be developed by the desired time. Besides establishing a balance between market-pull and technology-push strategies, this approach will also link the market drivers to technology drivers in cases where the required technology capability is nonexistent. Furthermore, this framework also analyzes the required resources to address the technology gaps and the risks associated with new technologies development. This goal can be achieved by integrating the fast-start process model (a moderately directed market-oriented approach), TRIZ (an exploratory and technology-oriented approach), and other strategic planning, decision-making, and risk assessment tools.

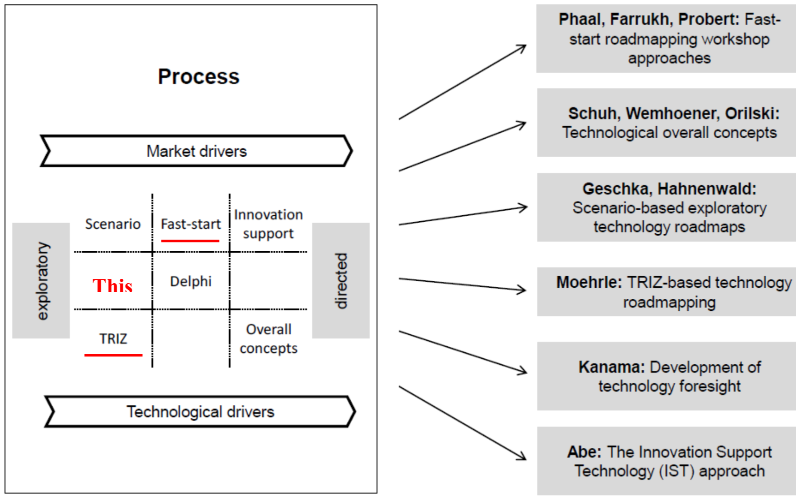


Figure 1.1. Processes for successful technology roadmapping [7]. Adopted from R. Phaal et al. (2013).

1.2. Objectives

The objectives of this research are three-fold:

a) Strengthening the linkage between market drivers and technology drivers in exploratory and technology-oriented roadmaps to have a balanced market-pull and technology-push strategy. This objective is achieved by integrating the TRIZ process model (exploratory and technology-oriented approach) with the fast-start process model (moderately directed and market-oriented approach)
b) Developing a robust TRM process through quantitative analysis and decision-making means. This objective is achieved using analysis grids (Quality Function Deployment) for linkage analysis and the Analytic Network Process for decision-making.
c) Analyzing the risk factors associated with roadmap elements and their impacts. This objective is achieved by applying Vectorized Bayesian Network to the elements of the roadmap.

1.3. Contributions

As a result of this study, a framework was developed for initiating and implementing TRM by enhancing the T-plan approach, a planning and process management method initially proposed by Phaal et al. [5]. Through this framework, a balance can be achieved between market-pull and technology-push strategies. Moreover, TRIZ was successfully incorporated in the enhanced T-plan process model.

In addition to structuring the TRM process, this research successfully integrates the Analytic Process Network with the framework to facilitate multiple critical decision-making stages throughout the process.

Finally, this research addresses the risk factors associated with a technology roadmap by incorporating a Bayesian Network and enhancing it with corresponding weight vectors. Therefore, the risk events, consequences, and impacts can be analyzed, and adaptive action plans can be discussed.

1.4. Dissertation outline

The first chapter of the dissertation provides an overview of the research's motivation, objectives, and achievements. Chapter 2 provides an exhaustive literature review of TRM and discusses the concepts and backgrounds of the other relevant topics to this research. Chapter 3 introduces and explains the conceptual framework developed in this research. It goes through every step and provides a guideline for applying the framework in different contexts. This chapter includes a description of roadmapping initiatives and how TRIZ is integrated into every step of the process. It also discusses how the drivers for each layer of the roadmap translate to the drivers of the next layer through analysis grids. Moreover, it illustrates how alternative solutions can be ranked through ANP and how the risk propagation is assessed throughout the network by using a Bayesian Network. It will eventually describe the integrated robust process model developed in this research. Chapter 4 describes the research methodology. It illustrates the purpose of the study, the research design, and the limitations and assumptions of the study. The developed framework was applied to an explanatory case study for developing an ice-phobic coating solution funded by Bell Textron Canada Limited. Therefore, Chapter 5 presents the results and the outcomes of the case study. Chapter 6 summarizes the findings and discusses the outcome of the case study. It will also provide implications and suggest paths for further research and innovation.

Chapter 2

Literature Review

2.1. Introduction

The theoretical framework section of this research follows a thematic structure. It is organized into four subsections that address different aspects of the topic. The first subsection presents an exhaustive literature review of TRM as the core topic of this research. It discusses the concepts of TRM, its research background, applications and benefits, the roadmapping process, and limitations.

One of the TRM limitations addressed in this research is the lack of reliability and objectivity, as well as unfocused and unclear boundaries [13] [14] [15]. As addressing these limitations required a designed thinking method to minimize subjectivity and establish focus and boundaries, TRIZ (Theory of Inventive Problem Solving) was adopted to enhance the roadmapping process. Therefore, the second subsection presents a literature review of TRIZ. It explains TRIZ's background and concepts. It also presents TRIZ's main process, tools, and techniques. Moreover, it discusses the integration of TRIZ and TRM and how the roadmapping process can benefit from TRIZ.

While the integration of TRIZ and TRM enhances the process to a more robust and structured one, to increase reliability, the TRMs should involve quantitative analysis as well. When quantitative data is involved, it is essential to consider the complexity and uncertainty of environments. Over the past few decades, systems' complexity has considerably increased, and according to the technology trends, systems will be getting more and more complex in the future [16]. Therefore, decision-makers and problem-solvers are facing more uncertainties from different viewpoints. Especially when facing an uncertain future, they need to have reliable approaches for forecasting. It is important because assumptions and best guesses might no longer be appropriate considering the increasing complexity, uncertainty, and multiple plausible future states [17]. As market drivers, products, and technologies evolve every day, TRM is also subject to these uncertainties. This research proposes a risk-adaptive TRM process model using a Bayesian Network. Therefore, the third subsection of the literature review presents the background of risk management in TRM and the concepts of conditional probability and the Bayesian Network.

The process of TRM is bound with decision-making in different stages. As multiple criteria are involved in every decision-making in TRM, a multi-criteria decision-making method is required. This research proposes to use the Analytic Network Process (ANP) for this purpose during the roadmapping process. Moreover, this research discusses the integration of ANP and Bayesian Network in weighting the network nodes with the output of ANP, resulting in an extended Bayesian network with weight vectors. Therefore, the fourth subsection of the literature review explains the concepts and process of ANP and presents an integration of ANP and Vectorized Bayesian Network (VBN).

2.2. Technology Roadmapping

2.2.1. What is Technology Roadmapping?

Technology roadmapping is a needs-driven flexible technology planning process [1] [18]. This approach helps companies and industry sectors to identify, select, and develop technology alternatives considering their customer needs in terms of products and services. TRM brings experts together as a team to develop a framework investigating the critical technology-planning information to make appropriate technology investment decisions and leverage those investments [1].

The TRM process provides a company with a pathway to develop, organize, and present critical system requirements and performance targets based on a given set of customer needs. Moreover, TRM arranges these system requirements and performance targets to be satisfied by a certain time frame. The technologies that need to be developed to meet the targets and satisfy the requirements can be identified by TRM as well. Furthermore, TRM can be taken advantage of when coming to the trade-offs among different technology alternatives that could be adopted as a potential response to the needs [1].

The roadmapping approach can be adopted at both the corporate level and industry-wide level. There are similarities and differences between the two levels. The structure of the roadmaps is similar at corporate and industry-wide levels. However, levels require different time commitments, costs, levels of effort, and complexity. The degree of detail in two different levels of roadmapping is not necessarily the same either [1].

TRM was initially developed at Motorola to improve the alignment between technology and innovation [19]. However, it is claimed that this approach was used before Motorola introduced it by Intel, which kept some of their technological secrets. The application of TRM became popular during the last two decades as it was adopted more and more by companies, industries, other institutions, and even governments [20]. The roadmapping approach consists of two main components. The first component is the application of TRM (i.e., the roadmapping process), and the second component is the result of the application (often in the form of a graphical map known as the roadmap) [4]. Therefore, the roadmap can be considered a summary of science and technology plans in the form of a map, and the process of developing this map is known as roadmapping [21]. There are different types and forms of roadmaps. However, it usually includes a multilayer graphical representation of a plan illustrating the connection between technology and product as well as market opportunities (see Figure 2.1) [2] [3].

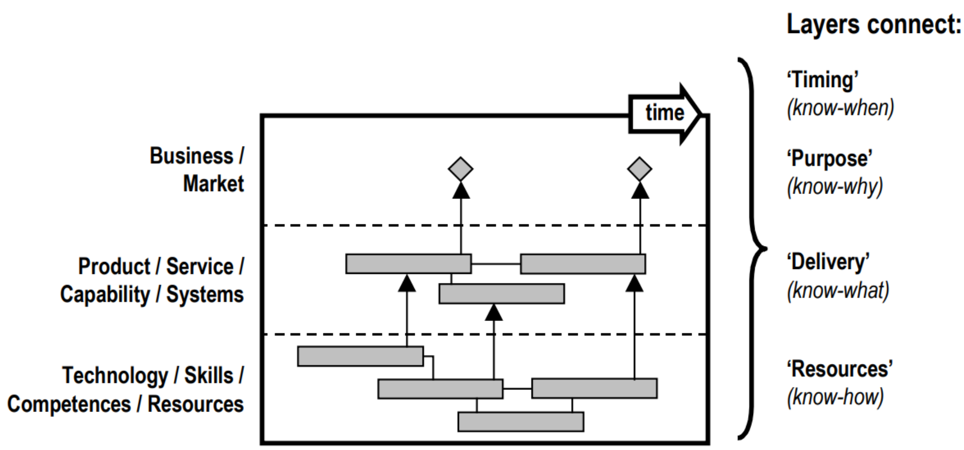


Figure 2.1 Generalized technology roadmap architecture. Adopted from Probert et al. (2003).

The time perspective considered in the TRM approach can vary from industry to industry based on the industry type and its planning horizon [2]. The benefits of the roadmapping approach are not limited to the result of the application. A significant part of its benefit is related to the dialog and communication during roadmapping, and it is sometimes even more critical to organizations [22]. For a higher chance of success in roadmapping, a company should have been previously identified the business threats [23].

The key characteristic of technology which is the main reason that it is distinguished from general types of knowledge, is that technology is applied and focused on the "know-how" of the organization (a planning framework) [18]. Technology usually concerns science and engineering ('hard' technology); however, the effective application of technology and the processes enabling it are also important ('soft' aspects of technology, i.e., organizational new product development and innovation process, alongside with organizational structure and supporting knowledge networks).

For reviewing the literature on TRM, it is helpful to look into the topic of technology and technology management as a broader field of science and practice. There are various definitions proposed for technology management in the literature [24] [25]. Among these definitions, the one proposed by the European Institute of Technology and Innovation Management (EITIM) fits the purpose of this report: "Technology management addresses the effective identification, selection, acquisition, development, exploitation, and protection of technologies (product, process, and infrastructural) needed to achieve, maintain [and grow] a market position and business performance following the company's objectives" [26]. The first important technology management theme of this definition is that companies must establish and maintain the linkage between technological resources and strategic objectives. This issue that has been a continuing challenge for firms requires effective communication and knowledge management, together with the support of appropriate tools and processes. The second theme highlights the importance of identification, selection, acquisition, exploitation, and technology protection [27].

The main processes addressed by technology management are the processes needed to maintain a stream of products and services to the market. Therefore, all aspects of integrating technological issues into business decision-making are investigated in technology management. Moreover, technology management is directly related to business processes such as strategy development, operations management, and innovation, and new product development [18]. Therefore, establishing appropriate knowledge flows between commercial and technological perspectives of a company is the key to having healthy technology management. As a result, the company can balance market pull and technology push strategies. Figure 2.2 illustrates the technology management process (identification, selection, acquisition, exploitation, and protection) and business processes (strategy, innovation, and operations), highlighting the needed dialogue between commercial and technological functions to support effective technology management.

Another critical aspect of business planning is the effective integration of technological considerations into business strategy. Technological resources must be considered as an integral part of business planning so that the technology strategy will not be developed independently from the business strategy [28] [29]. Prahalad and Hamel [30] suggest that the only way to fully realize the potential that a company's core competencies create is to envision markets that do not yet exist.

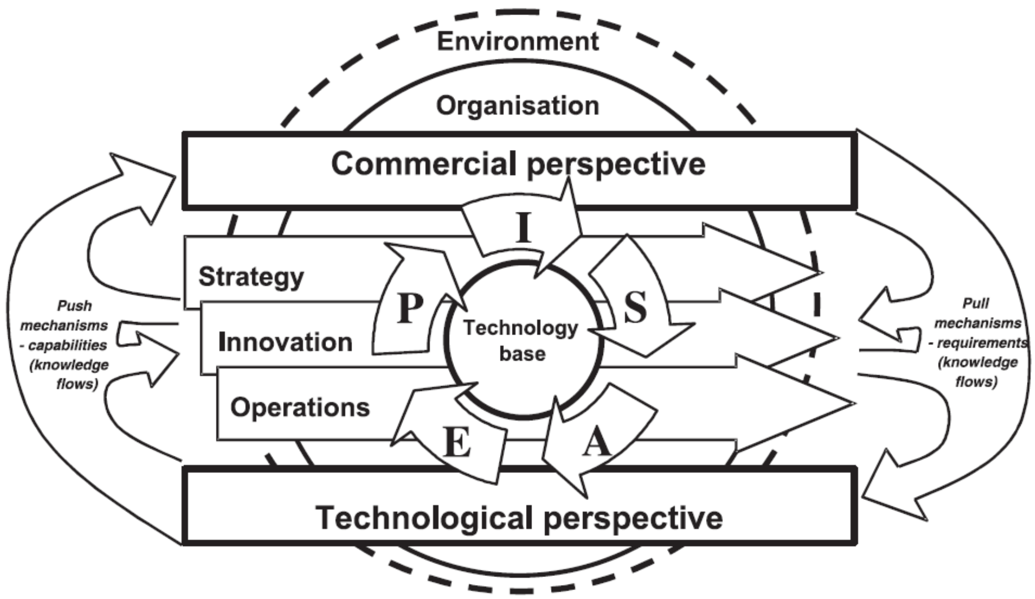


Figure 2.2. Technology management framework [31]. Adopted from R. Phaal et al. (2004).

Effective technology management must consider both external factors (i.e., nature of technological change and competitor activity) and internal factors (i.e., technological capabilities). Three key questions were proposed by Johnson and Scholes [32] to stimulate the development of a business strategy:

- **What basis?** which concerns selecting the generic strategic approach (i.e., cost leadership, differentiation, or focus)
- **Which direction?** which concerns identifying and selecting the alternative directions (i.e., doing nothing, consolidation, product development, market penetration)
- **How?** which concerns identifying and selecting the alternative methods (i.e., acquisition, internal development, joint development)

To answer these questions properly, a company needs to bridge the gap between market and technology opportunities and developments.

Another primary reason that technology management is a necessity for technology-based companies is the importance of technology transition. We can consider an S-curve for technology, representing technical performance as a function of time or research effort. At the same time, its shape is influenced by market demand, scientific knowledge, and level of innovation and investment [33] [34]. As the technology matures over time, it becomes impossible to make substantial improvements in performance due to economic or technical constraints. This stage can be considered as the time that the technology has reached the top of its S-curve. At this point, potential technology alternatives start to compete, resulting in the turbulence of the business environment until a new dominant design emerges. As the S-curves of different technologies are not linked, this can be considered a technological discontinuity [35]. Because managing technology transition is a delicate and challenging task [36], it must be done flawlessly if the company is about to survive the associated turbulent environment.

Considering all aspects of technology management and its importance, a highly dynamic vision of the future is vital for companies. Many approaches have been published in this regard, but an increasingly adopted technique for developing technology strategy and management in recent years is TRM.

The first paper presenting roadmapping was published in 1997. However, a significant increase in the number of papers in this area only started in 2004. A considerable portion (50%) of the papers related to roadmapping was published in just two journals: “Technological Forecasting and Social Change” and “Research-Technology Management” (see Appendix A, Table A.1) [4].

Also, in terms of the level of analysis, almost 52% of the articles consider TRM from the perspective of innovation and new product development containing aspects of innovation such as technology, management, Research and Development (R&D), and New Product Development (NPD). At the same time, 48% of the publications have been looking into TRM from the strategy and business perspective. Moreover, evidence shows that the research methods of the majority of the studies have been qualitative approaches. Thus, it is proof of the fact that TRM is still being explored and consolidated. Therefore, it is not a surprise that most of the published articles in this area of research are based on case studies (see Appendix A, Table A.2) [4].

Because the increased studies and publications related to TRM started in 2004, only a few papers about this approach were cited before that time. These papers are limited to Groenveld [37], which was the most cited, Coates et al. [38], Kostoff and Schaller [21], and Kappel [39]. Groenveld [37] investigated the initiatives of roadmapping at Philips Electronics, focusing on the early stages of the new product development process, and figured out that there was a considerable improvement in the integration between business strategy and technology management of the company through the roadmapping approach. Coates et al. [38] focused on analyzing roadmapping in the context of technological forecasting. Kostoff and Schaller [21] worked on identifying the intrinsic characteristics of the roadmaps to apply them more effectively, and Kappel [39] investigated the effects of roadmapping and ways to measure the identified effects and impacting factors.

Lee and Park [40] discussed the customization of the roadmapping process to consider forecasting, planning, and administration. The study conducted by Petrick and Echols [41] investigated the application of TRM in assisting investment decisions for new product development. Albright and Kappel [42] found roadmapping beneficial in the process of creating an information database related to product characteristics and in decision-making about the adopted technology and the targeted market. Porter et al. [43] presented roadmapping as an essential tool for analyzing the future of technologies. Walsh [44] worked on disruptive technologies, and Kostoff et al. [45] investigated the advantages and disadvantages of the roadmapping approach in creating cheaper and better products and services. Analyzing the literature related to hydrogen energy transition management, McDowall and Eames [46] figured out that a roadmap can be a tremendous help for long-term planning addressing the uncertainty associated with it. Finally, t study of Paal et al. [18] investigated the application of roadmaps as a tool to integrate the development of technologies with the business planning of a company, identifying the presence of threats and opportunities.

2.2.2. Applications and Benefits of TRM

TRM is a beneficial technique and has potential uses at the corporate and industry-wide level [1]. As one of the most important issues in companies is to have a clear idea about their technological needs and requirements, TRM can help develop a consensus about these needs. Moreover, this technique provides a structured mechanism to help specialists and experts from different company departments forecast technology developments in the areas targeted by the company. Furthermore, TRM can provide a company or an industry sector with a framework to plan and coordinate technology developments [1].

As mentioned earlier, apart from the result of the TRM approach (the roadmap), one of the most important benefits of this technique is that it provides experts with valuable information, helping them make better technology investment decisions. TRM helps identify critical technologies and technology gaps that the company needs to fill to meet product performance targets. Also, it helps with coordinating research activities within a company or an industry sector, leading to the best result from R&D investments. Besides, TRM can be considered as a marketing tool as well. A technology roadmap can be a reasonable interpretation of how a company understands customer needs. Also, it shows if a company can respond to customer needs by itself or through alliances by developing the necessary technologies [1].

TRM is being undertaken by some companies as one aspect of their technology planning. At the industry level, however, TRM is not limited to only one single company. Instead, companies in the same industry sector can focus on common needs, address the research required more effectively, and collaborate on developing mutual technologies. This way, an industry develops the key technologies collaboratively, and individual companies would not fund the same research redundantly while underfunding or missing other potentially essential technologies. Moreover, a particular technology may be too expensive to be invested in by a single company or may take too long to develop. Therefore, collaborative development can be significantly beneficial. When adopting this approach, however, the competitive considerations of the industry should be taken into account [1]. Figure 2.3 shows a comparison between the adoption of TRM in various sectors.

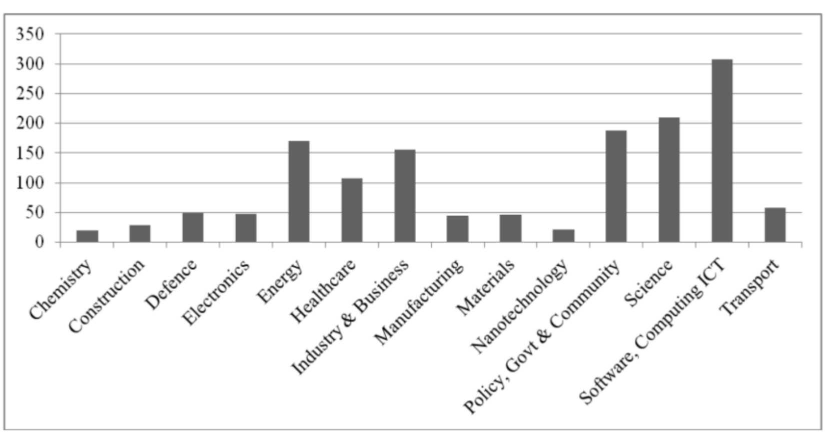


Figure 2.3. Public domain roadmaps from various sectors. Adopted from Amer and Daim (2010) [47].

2.2.3. Technology Roadmap

A technology roadmap is the result of the TRM process that is presented as a document. It identifies the critical system requirements, the product and process performance targets, and the technology alternatives for a particular set of needs. It also identifies the milestones for meeting the targets. After the roadmapping investigation, one of the alternative paths may be selected, and the company can develop a corresponding plan. Of course, the risk and uncertainty should be taken into consideration in certain environments. Therefore, in high-risk environments, companies come up with multiple paths and pursue them simultaneously. The roadmap helps companies identify clear and precise objectives and make decisions on dedicating resources to the critical technologies needed to be developed or adopted to meet those objectives. It should be considered that the R&D investments are limited, and it is important to focus them on the right technology.

2.2.4. Types of Technology Roadmaps: purpose, format, and use

As mentioned before, one of the main advantages of TRM is its flexibility. This flexibility becomes essential when the technique is to be adopted for different organizational aims. Also, the wide range of graphical forms that a roadmap can take allows companies to present the result of their roadmapping process in the form that works best for their company. Based on different potential uses of the roadmapping approach, it may be called product, innovation, business, or strategic roadmapping. According to an examination of a set of approximately 40 roadmaps, the range of different roadmap types has been clustered into 16 broad areas (see Figure 2.4). These groups - which will be described in more detail in the following section- reflect both the intended purpose and the graphical format of roadmaps [48].

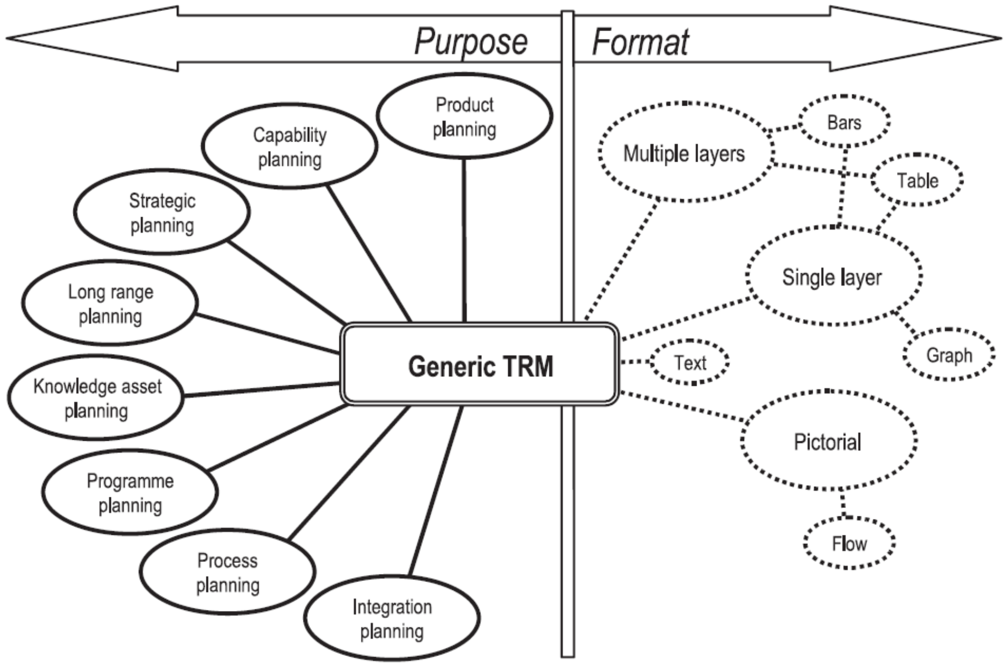


Figure 2.4. Characterization of roadmaps: purpose and format [49]. Adopted from R. Phaal et al. (2003).

2.2.5. Purpose of TRM

a) **Product planning:** This can be considered the most common type of technology roadmap. It mainly investigates the insertion of technology into manufactured products. The product set can include more than one generation of products. A Philips roadmap can be a good example of this approach being adopted, and the links between planned technology and product developments are shown [37] (see Appendix A, Figure A.1(a)).

b) **Service/capability planning:** This type of roadmap is more suited for the companies providing services rather than producing products. Service/capability planning roadmaps focus on how technology can support the capabilities of an organization. A Royal Mail roadmap is shown in Appendix A, Figure A.1(b), investigating technology development impact on the business based on an initial T-plan application [50] (more on T-plan in the following section).

c) **Strategic planning:** The main application of this roadmap type is for general strategic appraisal. A strategic planning roadmap helps a company by evaluating different opportunities and threats at the business level. A roadmap developed by T-plan and to support strategic business planning is shown in Appendix A, Figure A.1(c). The main focus of this type of roadmap is developing a vision of the future business. Aspects such as markets, businesses, products, technologies, skills, and culture will be considered in this roadmap type. Moreover, this roadmap helps identify the gaps by comparing the future vision and the company's current state. Finally, the alternative strategies to bridge the gaps will be explored.

d) **Long-range planning:** The main application of this type of roadmap is to support long-range planning with an extended planning horizon. Therefore, this type of roadmap is mainly at the sector or national level. As it helps identify potentially disruptive technologies and markets, it can be considered a radar for the organization. The U.S. Integrated Manufacturing TRM Initiative has developed a series of roadmaps. One of these roadmaps is shown in Appendix A, Figure A.1(d), focusing on the information system [51]. The roadmap presents how technology developments are converging towards the 'information-driven seamless enterprise.'

e) **Knowledge asset planning:** This type of roadmap is suitable for aligning knowledge assets and knowledge management initiatives with a company's objectives in a market. Appendix A, Figure A.1(e) shows a roadmap developed by the Artificial Intelligence Applications Unit at the University of Edinburgh [52]. The roadmap enables organizations to have a clear idea about their critical knowledge assets by visualizing them and understanding the linkages to the skills, technologies, and competencies needed to meet the demands of the future market.

f) **Program planning:** This type is directly related to project planning, and its focus is on implementing the strategy. Out of many roadmaps developed by NASA for the Origins program, Appendix A, Figure A.1(f) shows one which investigates how the universe and life within it has developed. This particular roadmap mainly focuses on managing the development program for the Next Generation Space Telescope (NGST). It indicates the relationship between the development of technology and the phases. It also indicates the milestones of the NGST development program.

g) **Process planning:** This type is mainly suitable for knowledge management of a particular process area (i.e., new product development). Appendix A, Figure A.1(g) presents a roadmap focusing on the needed knowledge flows to facilitate effective new product development and introduction, developed using T-Plan. This type of roadmap incorporates both technical and commercial perspectives.

h) **Integration planning:** This type of roadmap focuses on how different technologies combine within products and systems. Therefore, it provides a good overview of the integration and/or improvement of technology. They can also come into use when forming a new technology. These roadmaps do not necessarily show the time dimension explicitly. A NASA roadmap is shown in Appendix A, Figure A.1(h), related to NGST development program management and focused on technology flow. It shows how technology is the first ring of scientific missions by feeding into test and demonstration systems.

2.2.6. Format of Technology Roadmaps

Technology roadmaps have been clustered in eight types in terms of graphical format:

a) **Multiple layers:** Multiple layer roadmap is considered the most common format of TRM used by organizations. It contains several layers and sublayers and shows each layer's evolution, helping experts explore the evolution of the subject each layer corresponds to (i.e., technology, product, and market). It also shows the interlayer relation and dependencies to facilitate integrating technology into products, services, and business systems. For example, a Philips roadmap [37] is shown in Appendix A, Figure A.2(a), supporting the integration of their product and process technologies to develop future product functionality.

b) **Bars:** Each layer or sublayer can be expressed in the form of a set of bars. As the bars simplify and unify the required output, it is a considerable advantage for the integration of roadmaps, facilitation of communication, and the development of software to support roadmapping. A Motorola roadmap [19] shown in Appendix A, Figure A.2(b) is an example of a bar roadmap related to the evolution of car radio product features and technologies.

c) **Tables:** As the roadmap is a flexible graphical representation, the entire roadmap or layers within the roadmap can be presented as tables. (i.e., time vs. performance or requirements). This approach is beneficial, mainly when company performance can be expressed in numbers and presented in quantities or where activities are clustered in different time frames. A tabular roadmap can be seen in Appendix A, Figure A.2(c) [53], including product and technology performance dimensions.

d) **Graphs:** Graphs are another format of expressing a roadmap where product or technology performance is quantified. This type of graph is closely related to the technology S-curve; thus, it is sometimes called an experience curve. The way products and technologies coevolve [53] can be observed in Appendix A, Figure A.2(d).

e) **Pictorial representations:** More creative pictorial representations can be adopted in roadmaps to communicate technology integration and plans. Some metaphors, such as a tree, can also be used to communicate the idea. A Sharp roadmap [54] is shown in Appendix A, Figure A.2(e), investigating the development of products and product families, considering a set of liquid crystal display technologies.

f) **Flow charts:** Like many other techniques, the flowchart is a pictorial representation option for roadmapping. Flowcharts are mainly used to represent the relationship between objectives, actions, and outcomes. In Appendix A, Figure A.2(f), a NASA roadmap is shown, elucidating the relationship between the organization's vision and its mission, primary business areas, fundamental scientific questions, short-, mid-, and long-term objectives, and contribution to U.S. national priorities [55].

g) **Single-layer:** This type can be considered a subset of Type A and focuses on a single layer of a parent multiple-layer roadmap. Although it has the upside of being less complex, it misses the possibility of communicating inter-layer relations. An example of a single-layer type is the Motorola roadmap [19], which focuses on the technological evolution of a product and its features. Of course, the single-layer roadmap is supported by additional documentation and software linking it to the other layers constituting the multi-layer roadmap.

h) **Text:** Roadmaps can be entirely or primarily text-based as well. Text-based roadmaps describe the same issues and detail included in other graphical roadmaps. For example, the Agfa white papers text-based roadmap illustrates the technological and market trends that will influence the optics sector [56].

As observed, the wide range of roadmap types may mean that the methodology lacks clear and widely accepted standards or protocols for their construction. Therefore, it brings up the significant need to adapt the approach to suit the organization's business purpose, existing sources of information, available resources, and desired use [18]. However, it cannot be necessarily considered a disadvantage because some companies might prefer to adapt the technique with their processes and, therefore, consider it a privilege. Moreover, roadmaps do not always fit in the clusters and categories identified in most common approaches perfectly. Therefore, depending on the organization, there needs to be flexibility in both purpose and format, resulting in hybrid forms.

2.2.7. Use of TRM

According to a survey of 2000 UK manufacturing companies [57], about 10% of most large companies have applied TRM. From those companies, approximately 80% are either using the technique more than once or taking advantage of it on an ongoing basis. The application of TRM, however, comes with considerable challenges for organizations. Despite the fairly simple concept and structure of the technology roadmap, representing the summarized final outputs from the planning and roadmapping process, there have been key challenges reported by the firms applying roadmapping. Fifty percent of responding companies have declared keeping the roadmapping process "alive" and consistent as a key challenge. At the same time, 30% believed the key challenge to be starting up the TRM process, and the rest have reported developing a robust TRM process as their key challenge.

As discussed before, having a wide range of specific formats is one of the main reasons companies struggle with the application of TRM. As a result, companies often have to adapt the roadmapping approach with their specific need and business context. Furthermore, despite some efforts to share the area's experiences, there is little practical support available for the approach. Therefore, the companies have no choice but to reinvent the process. As examples of these efforts on indicating the development of an effective roadmapping process within a business, Bray, and Garcia [58], EIRMA [53], Groenveld [37], and Strauss et al. [59] summarize key TRM process steps. These authors, however, do not include a detailed guideline or a step-by-step procedure to apply the approach. T-Plan is an attempt to fill this standard process gap as a fast-start approach and will be discussed later in this report.

2.2.8. TRM Process

This section presents an overview of three major phases of the TRM process (see Figure 2.5 and Appendix A, Figure A.3).

Phase I. Preliminary Activity (Preparation)

1. Satisfy essential conditions
2. Provide leadership/sponsorship
3. Define the scope and boundaries for the technology roadmap

Phase II. Development of the Technology Roadmap (Operation)

1. Identify the "product" that will be the focus of the roadmap
2. Identify the critical system requirements and their targets
3. Specify the major technology areas
4. Specify the technology drivers and their targets
5. Identify technology alternatives and their timelines
6. Recommend the technology alternatives that should be pursued
7. Create the technology report

Phase III. Follow-up Activity (Revision)

1. Critique and validate the roadmap
2. Develop an implementation plan
3. Review and update

Figure 2.5 The three phases in the technology roadmapping process [1].

Phase I. Preliminary Activity

The initial phase is focused on preliminary activities that are necessary for developing the roadmapping approach. In the first phase (see Appendix A, Figure A.4), the key decision-makers and parties of the problem come together to discuss, realize and perceive the problem they are facing for which they are developing a technology roadmap. They need to decide and have a clear idea of what will be roadmapped and how the technology roadmap will help the experts with their investment decisions. Therefore, one of the most critical issues for decision-makers is accepting the procedure and being willing to use it. As a result, the resources needed for creating the roadmap will be provided. Moreover, as the roadmapping process is typically ongoing and iterative based on the scope, the buy-in of the decision-makers and involved parties needs to be maintained.

Like any other group activity, there is always a chance that all the parties are not satisfied as they expect different results. It can lead to a complication that should be avoided for the roadmapping process to be successful. Of course, at least partial satisfaction of all the parties and decision-makers should be met. The steps of this phase are to make sure that the essential buy-in for the entire roadmapping process is obtained. This acceptance should be maintained throughout the later phases as well [1].

1. **Satisfy essential conditions**

There are several essential conditions to be satisfied for a successful TRM effort (see Appendix A, Figure A.5). This step ensures that those conditions are either already met by the parties or the experts involved will take necessary actions to meet the conditions. Despite being similar, the required conditions are not identical, and they have slight differences for corporate- and industry-level TRM:

- The need for TRM and collaborative development must be clear and perceived by every single party of the roadmapping team. Of course, a broader group of experts need to come to a consensus for industry-level roadmapping.
- TRM needs the participation and information input of several groups of experts and cannot be applied by only one department of an organization. Moreover, the participation of several groups and departments in roadmapping brings different perspectives and a universally accepted planning horizon to the roadmapping process.
- Along with the participation of different groups and departments of a company (i.e., R&D, marketing, manufacturing, planning), the participation of a selected group of key customers and suppliers is necessary.

- In industry-level TRM, the support and participation of government and universities need to be added to the members of the industry, its customers, and suppliers.
- The company policy must be clear about whether to have a technology push, a need-driven pull, or a hybrid approach. The scope of the technology roadmap must be clear, and the boundaries of the effort need to be specified. Finally, the company must have a clear view of how the roadmap will be used.

2. Provide leadership/sponsorship

There will be a significant amount of time and effort involved in the roadmapping process. Therefore, there is a severe need for committed leadership and sponsorship. Of course, it is the best choice to have the leadership and sponsorship from the group in charge of implementing the roadmapping approach who benefit from it. In corporate-level roadmapping, the line organization can lead the roadmapping process to make effective investment decisions. In industry-level roadmapping, the industry is the best choice for leading the effort. In the meantime, the support and participation of customers, suppliers, government, and universities are necessary. Development, validation, and implementation of roadmapping needs to be done with the participation of all the parties at the industry level.

3. Define the scope and boundaries for the technology roadmap

A company applying TRM techniques must make sure that it has a clear understanding of the context of roadmapping. It is necessary to ensure that a clear vision has been developed (at the corporate-, or industry-level) and that the roadmap can support that vision. A deep understanding of roadmapping context helps identify the need for TRM applications and how to use it after it is developed. Moreover, it specifies the scope and boundaries of the roadmap.

The time horizon of roadmaps depends on the intention of their development and varies based on organization and industry. However, the time horizon for industry-level roadmaps is typically at least 10 to 15 years while having short-term milestones. On the other hand, the time horizon for corporate-level roadmaps may be shorter.

Defining the scope and boundaries of TRM is an essential step at both the corporate-, and industry-level. Nevertheless, the complexity is more in industry-level roadmapping, and the step would be more complex and time-consuming.

- Roadmapping starts with a certain set of needs. However, there are many levels of needs, and roadmapping teams must decompose them. Also, the products, subsystems, and/or components involved in the developing roadmap can have different levels. All the participants must come to a consensus and commonality when selecting the levels.
- Inter-organization collaboration is not an easy job to do. Therefore, the steps of the first phase take significant learning efforts. In the meantime, the involvement of an industry umbrella organization can facilitate communication and improve the pace and efficiency of the process. In addition, the umbrella organization can have a contribution to providing resources as well.

Phase II. Development of the Technology Roadmap

This phase comprises seven steps (see Appendix 1, Figure A.6). Although these steps are similar for both corporate- and industry-level to create technology roadmaps, the resource and time requirements are significantly greater for industry roadmaps [1].

1. Identify the "product" that will be the focus of the roadmap

The participants of the roadmapping process must agree on common product needs that must be satisfied. Therefore, decision-makers must come into commonality about it as it leads to all participants' buy-in and acceptance about the roadmapping process. In addition, the roadmap may focus on many components and levels based on the complexity of the product. Therefore, it is critically important to select the appropriate focus.

In case of significant uncertainty about the product needs, companies can adopt a scenario-based planning approach. For example, in the context of an energy-efficient vehicle, one scenario can be based on a major oil find or a renewable energy technology breakthrough. As a result, there would be a drastic fall in the price of gas or other fuel. On the opposite, another scenario could be based on an oil shock drastically reducing the supply, resulting in a significant oil price hike. Each scenario must be internally consistent and reasonable. A scenario also needs to be comparable with the other scenarios which affect one or more needs considered in the roadmap.

Scenario analysis may need to be conducted, including extreme cases, while not overemphasizing them or letting them drive the roadmap. It is important to remember that scenarios are not certain occurrences. They are the only means to address the uncertainty of the environment and the needs, and the purpose of developing them is to improve the roadmap.

Scenarios are developed to provide a better understanding of the needs, services, or products. In many cases, the needs for all the scenarios are the same. However, there might be a unique critical need in a particular scenario with a highly considerable probability that cannot be ignored. The company can work on such cases and consider its efforts as insurance. It must also be considered that the needs' uncertainty level changes over time, and the emphasis on the related technology could increase or decrease consequently. Periodic reviews and updates of the roadmap can be beneficial for monitoring and managing such potential changes.

2. Identify the critical system requirements and their targets

The critical system requirements can provide the overall framework for the roadmap. Once the decision-makers and the participants of the roadmapping process have identified the needs to be roadmapped, the next step would be to identify the critical system requirements. As discussed in the energy-efficient vehicle example, the critical system requirements can include reliability, safety, mpg, and cost. The corresponding targets could be 70 miles per gallon (mpg) by 2010 and 85 mpg by 2020.

3. Specify the major technology areas

The key to achieving the critical system requirement for the product are the major technology areas. For example, regarding energy-efficient vehicles, the technology areas to satisfy performance targets (system requirement) of 85 mpg by 2020 are materials, engine controls, sensors, and modeling and simulation.

4. Specify the technology drivers and their targets

In the fourth step, the critical system requirements must be translated into technology-oriented drivers. The technology drivers for specific areas are important as they are the critical variables based on which the technology alternatives will be selected. For example, technology drivers could be acceptable engine temperature and vehicle weight in the materials technology area. On the other hand, for the engine control technology area, the technology driver could be the cycle time for the computer controlling the engine.

Technology drivers are not only dependent on the technology areas involved in the product, but they are also set based on the way the technology addresses the critical system requirement targets for the product. Therefore, targets must be set to specify if a viable technology alternative can perform by a specific time meeting the critical requirement and how well it can retain its performance. For example, considering meeting 85 mpg by 2020 as a system requirement, from the technology perspective, engine control technology needs to be able to adjust engine parameters every certain period of time, dealing with a certain number of variables. Therefore, it would require a processor with a certain cycle time as the technology driver target.

5. Identify technology alternatives and their timelines

As soon as the experts specify the technology drivers and their targets, the roadmapping team can identify the technology alternatives for satisfying those targets. If a performance target is difficult to reach, there may be a need for a breakthrough in more than one technology area. In the meantime, a remarkable breakthrough in one technology may impact multiple targets.

The goals will not be met unless the organization follows a specific timeline. Therefore, each identified technology alternative in the roadmap will need an estimated timeline for developing and maturing, considering the technology driver targets. In addition, the team might be considering the development of multiple technologies simultaneously. In that case, there must be decision points identified to decide if a technology alternative is considered the winner or it should be dropped from consideration.

6. Recommend the technology alternatives that should be pursued

After coming up with alternative technologies, the decision-making team needs to select a subset of alternative technologies to be pursued. The reason is that the technology alternatives vary in terms of schedule, cost, performance, and many other important factors. While one path may get the company to the critical system requirement faster, another may improve system performance over the target. Moreover, neither meeting the target nor the performance improvement would matter if the timeline for technology development does not fall within the critical path of the product/service development. In the meantime, of falling within the critical path of the product/service development, a faster path would mean a faster time to market as a competitive privilege. However, performance improvement over the target may be preferable for the company and worth the extra time or cost. In contrast, even doubling the performance might not add considerable value to the product/service if other factors such as time and cost become dominant constraints. Therefore, a thorough investigation would be needed to trade off the alternative technologies and select a subset. Depending on the situation, a company can pursue performance improvement considering technology metrics or modify product/service metrics based on a technology breakthrough.

The problem can potentially be even more complicated. In some cases, a particular technology may meet the first couple of technology driver targets but fail to satisfy the others. It can be the other way around. Another technology may not be meeting the immediate targets while being capable of satisfying the subsequent ones. The latter case is called 'disruptive technology' [34]. A technology is called disruptive when it cannot meet the immediate needs of system requirement, however, if developed, its performance and rate of improvement is much higher than current technology. Nevertheless, disruptive technology, which will eventually replace the current technology, is often ignored and underfunded. However, the broader perspective provided by a technology roadmap can bring it to the attention of decision-makers.

The trade-offs and decisions about which technology alternative to pursue and when and how to shift it to another (jumping to a new technology curve, i.e., a disruptive technology) must be made by the best judgment of the experts. However, in some cases, certain analytical and modeling tools or software can help in decision-making. Nevertheless, the roadmapping process has provided the experts with valuable information and consensus about their approach. Moreover, the TRM process has established a collaborative effort that will lead to more effective and efficient use of limited investment resources for technology when carried to implementation.

7. Create the technology report

By this point, the roadmapping team has developed the company roadmap(s). The roadmap report must include the following items (see Appendix A, Figure A.7):

- Clear identification and description of the involved technology areas and their current status.
- Critical factors, necessary to be met for the success of the roadmap.
- The areas which are not addressed in the roadmap.
- Technical recommendations.
- Implementation recommendations.

The roadmap report may also contain additional information about the competencies of alternative technologies in terms of potential performance improvement, time to market, and cost.

Phase III. Follow-up Activity

If the participants of the roadmapping process have come up with early buy-in and acceptance of the process in the first phase, the follow-up activities will not be tricky (see Appendix A, Figure A.8). Without this acceptance, however, the decision-makers would not have a clear idea about the issues that need to be resolved, and the roadmap cannot be effectively used in consequence. As the roadmapping team consists of relatively few people, the roadmap needs to be critiqued, validated, and accepted by a larger group of experts involved in any implementation. Once the roadmap is validated and accepted, an implementation plan must be developed based on the information generated through the TRM process to make an appropriate investment decision. As both the needs and technologies continuously evolve, the roadmap must be reviewed and updated periodically [1].

1. Critique and validate the roadmap

A draft of the roadmap(s) was developed by a relatively small group of experts and technologists in phase II. In this step, the developed roadmap or roadmaps -if multiple technologies and/or scenarios are involved- must be critiqued, validated, and accepted by a much larger group of experts (see Appendix A, Figure A.9):

- First, the developed roadmaps must be reviewed, and certain questions need to be asked:
    - If a company or industry has already developed the recommended technology alternative, will it meet the technology driver and consequently the system requirement targets?
    - If the recommended alternative technology is to be developed, is it reasonable?
    - Are all the necessary technology alternatives covered in the roadmap?
    - Is the roadmap clear and understandable (especially for the experts not personally involved in the roadmap development process)?
- Second, the buy-in from the broader potentially involved corporate or industry groups and experts must be assured to continue the process and implement the plan. To achieve the acceptance of the broader group of experts, the roadmapping team can hold structured workshops to provide feedback and bring all the participants to at least a partial consensus. Then, of course, the roadmap can be revised if needed.

2. Develop an implementation plan

At this point, the decision-makers have enough information to make an appropriate technology selection and investment decisions. Therefore, an implementation plan can be developed based on the recommended technology alternatives. However, the explicit coordination of different participants and departments and their responsibilities must be identified when developing an implementation plan. This responsibility assignment and coordination level identification may be more complicated when developing an implementation plan at the industry level.

3. **Review and update**

The developed technology roadmap(s) and implementation plan must be periodically/routinely reviewed and updated. Reviewing and updating the roadmaps and plans will be a formal iterative process. One of the main reasons for review and update is managing the uncertainty during the process. Once the initial roadmap is developed, the first uncertainty the team will face is the time frame. Moreover, going on through the process, as the experts explore and will have a better understanding of specific technologies, the uncertainty concerning those technologies reduces; however, other areas of uncertainty can always develop. Another area of uncertainty is about the needs. Suppose the roadmapping team has developed scenarios to address the uncertainty about the needs. In that case, they may need to consider refinement or elimination of some of the scenarios as the needs are subject to change continuously over time. The periodic review and update will allow the roadmap and the implementation plan to be adjusted for these potential changes. Depending on the experts' decision, the review and update cycle can obey the company's normal planning cycle or be based on the technology change rate.

2.2.9. T-plan Fast-Start TRM

Although there is no widely accepted standard process for implementing the TRM approach, a T-plan fast-start approach was developed as a result of a three-year applied research program. During the development of this approach, more than 20 roadmaps were developed collaboratively by various company types in several industry sectors [18]. Also, more recently, the general principles of the T-plan fast-start approach have been adopted to develop multi-organization roadmaps.

The T-Plan process contains two main parts:

1. Standard approach, which supports product planning
2. Customized approach, which can support broader applications of the method and provides guidance for that.

T-Plan standard process (product planning)

The standard T-plan process comprises four workshops, facilitating communication between experts. The first three workshops focus on the main layers of the common roadmaps (see

Appendix A, Figure A.2(a)) (market/business, product/service, and technology), and the approach is a need-driven process based on market and business requirements (see Figure 2.6).

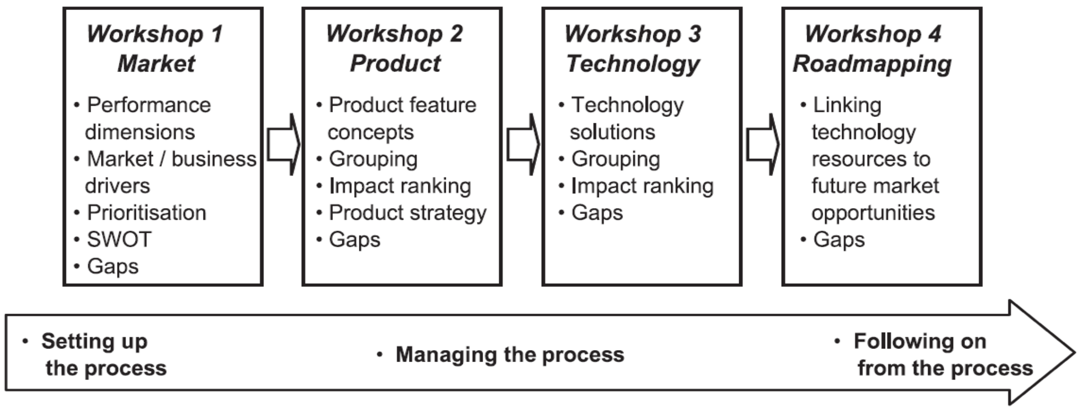


Figure 2.6 T-Plan: Standard process steps [18]. Adopted from R. Phaal et al. (2004).

The priority of product and technology alternatives are identified based on market and business requirements (as shown in Figure 2.1). Therefore, the process can be considered as a predominantly market-driven pull process; however, in the meantime, a company can aim to develop novel technology solutions to add more value to new products and seek new market opportunities.

Another important issue is the management of parallel activities while applying the T-plan approach. To have a successful T-plan application, the company must simultaneously and effectively manage the planning, facilitation of workshops, process coordination, and follow-up actions. The relationship between different layers and sublayers of the roadmap can be identified through linked analysis grids, similar to the quality function deployment (QFD) approach used in product and engineering design [60].

In the T-plan approach, the workshops work as veins and support the roadmapping initiative, while the system's blood is the inputs and outputs aligned with the process. Support is also required in terms of data collection, result analysis, facilitation, and project management. Regardless of how many workshops are required, Laat & McKibben separate the roadmapping initiatives into three broad elements: preparation, implementation, and follow-on [61]. Figure 2.7 illustrates the position of roadmapping initiatives and workshops within strategy and innovation processes.

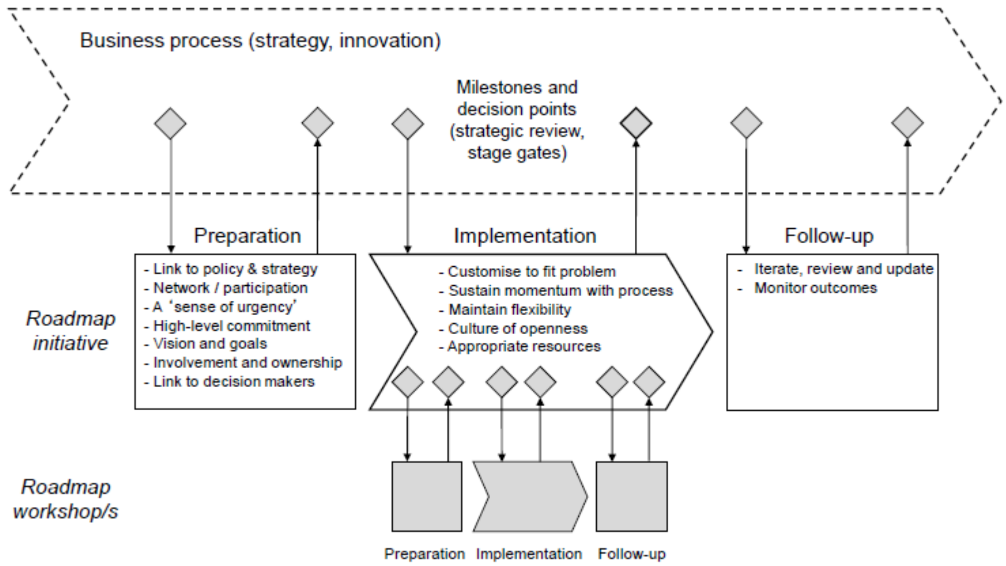


Figure 2.7 Position of roadmapping initiatives and workshops within strategy and innovation processes, highlighting key success factors [61]. Adopted from Moehrle et al. (2013).

Customizing the process

There is a wide range of different business aims that can be supported by roadmapping (i.e., product planning, resource allocation and management, exploration of new opportunities, and improved business strategy and planning). Also, each organization has its own organizational culture, business processes, business context, available resources, technology types. Therefore, the roadmap will provide the company with the greatest result if customized to suit a particular application in a particular company. As mentioned before, the multilayer roadmap is the most common form of roadmaps being used in industries and has the greatest flexibility in application. The dimensions of the multilayer roadmap are as follow:

a) Time: Time dimension can be used in different forms adapting to suit the company's particular situation. Typically, in terms of time horizon, sectors such as e-commerce and software have considerably shorter time horizons than aerospace and infrastructure sectors. A logarithmic scale is typically used to represent the time on the roadmap, having more space allocated to the short-term for identifying more detail while smaller space for the long-term; however, the company can always choose to have a continuous time scale. Moreover, different intervals can be used in a roadmap (i.e., six months, annual, or short-, medium- and long-term). The time-space on a roadmap can also be allocated based on business vision and very long-range consideration, in addition to the current situation and the history (past time). This approach can help identify the gap between the company's current status in the business and its vision.

b) Layers: Layers are represented through the vertical axis of the roadmap. They are critically important because they must be designed based on a particular organization and the problem. Therefore, a significant part of the initial effort of roadmapping is often dedicated to defining layers and sublayers. The generic architecture of a roadmap can be seen in Figure 2.8.

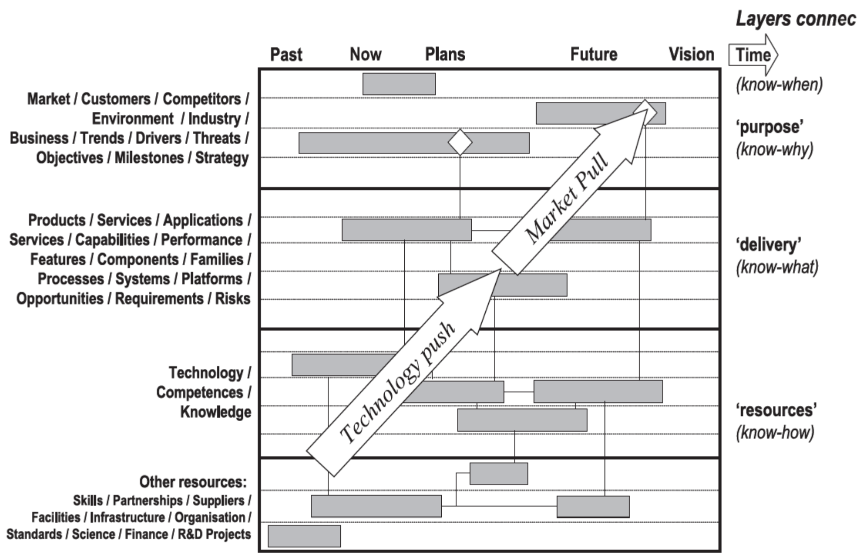


Figure 2.8 Generic technology roadmap architecture. Adopted from R. Phaal et al. (2004).

The possibility of defining different layers and sublayers gives the roadmap flexibility in providing a framework for the organization's strategic planning. The top layers are related to the organization's purpose. The purpose of the organization is considered as the drive of the roadmap (know-why). The bottom layers concern the resources (technology knowledge, particularly in this context). This resource addresses the roadmap drive, which is the demand needs from the top layers (know-how). Finally, the middle layers play the role of a bridge between the top layers and bottom layers. The goal of the middle layers is to provide a delivery mechanism between the purpose and resources (know-what). The focus of the middle layers is frequently on product development, as this is the path through which technology deployment often meets market demand and customer needs. However, depending on the purpose of roadmapping and the business situation, services, capabilities, systems, risks, or opportunities may be the appropriate delivery mechanism and fit the middle layers.

c) Annotation: The roadmap can store other information on a timely basis and is not necessarily limited to the information contained within the layers. A roadmap can also contain:

- o Linkages between objects in layers and sublayers
- o Supplementary information (i.e., a key statement of business strategy, market drivers, people involved in roadmapping process, assumptions)
- o Other graphic devices (i.e., objects, notes, color coding) to indicate milestones, key decision points, critical paths, gaps, opportunities, and threats (including disruptive technologies and markets).

d) Process: For completing the first roadmap and taking the process forward, certain steps are required. However, these steps are typically different for each organization. There may even be differences within an organization when different departments are involved. The suitable process is dependent on many factors such as level of available resources (budget, time, people), nature of the problem being investigated (purpose and scope), available information (market and technology), and other relevant process and management methods (strategy, budgeting, new product development, market research, project management). Strategic planning considers both the external view of the firm (market and business environment) and the internal view (tangible and intangible assets) and brings them into balance. Through the roadmap, these external and internal perspectives (opportunities, threats, strengths, and weaknesses) will be integrated, and the company will be provided with a set of product-technology options to consider (see Figure 2.9).

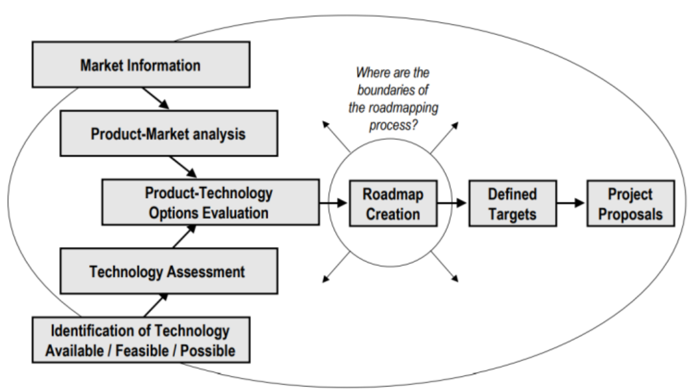


Figure 2.9 Roadmaps integrate commercial and technological knowledge [30]. Adopted from R. Phall et al. (2004).

Therefore, most of the roadmaps include aspects of both market pull and technology push. As shown in Figure 2.8, it is understandable from the direction and rate of technology, product, and market development that there is a balance between these drivers. However, this is important that technology push is generally a more complex and divergent approach than market pull. The reason is that a particular technology may have multiple applications in different domains, and there is no necessity that the firm has sufficient experience in all those domains. Therefore, although most customized T-plan applications had the conclusion that a combination of market pull and technology push would have the best result, the firms generally prefer to develop their strategic plan in a market-oriented fashion.

The most important consideration for customizing the roadmap and roadmapping process is the planning phase. In the planning phase, the process objectives must be clearly articulated. The roadmapping team must think through how the generic process of roadmapping will help the organization achieve its objectives. Another critical issue is the ownership of the roadmap. The roadmap is firstly owned by a single designated person or group of people (committee or steering group) and then by the other experts involved in the creation of the roadmap. Ultimately, the roadmap is owned by the entire organization developing the roadmap as a communication tool. The person or group of people designated to manage the process and facilitate the workshops may need to bring in expertise related to technology fields, markets, or industries from outside of the organization. It will help the organization to have a broader view of the problem and potential opportunities and threats.

Although the T-plan was primarily developed from a company perspective, the method can be customized for multi-organizational use. It will help the industry to have a better view of the environmental landscape, threats, and opportunities for the industry stakeholders.

Roadmapping can be considered as a focal integrating device to carry the business strategy and planning process forward. This technique brings the internal perspective (market/commercial) and external perspective (technological knowledge) of the organization together (see Figure 2.9). However, for a successful implementation of the roadmapping process, the company must know where the boundaries of the roadmapping process should lie, to what extent the method should be adopted, and how to integrate this technique with other systems and processes.

2.2.10. TRM Key Challenges

There are two major challenges in the way of successful implementation of the roadmapping process:

i. **Keeping the roadmap alive:** The best result of roadmapping is achieved only if the roadmap information is kept up-to-date over time. Therefore, the roadmap needs to be updated periodically based on budget or strategy cycles. It might need to be updated even in shorter periods, depending on the nature of business and addressed issues. The initially developed roadmap needs to be captured, stored, communicated, researched, and updated (and revised if necessary). Thus, careful consideration of the process and system is required by the TRM team.

ii. **Roll-out:** As the roadmap is developed, it must be adopted by other parts of the organization. Adoption of the roadmap by other organization departments must be facilitated. There are two approaches for rolling out the method:
   - **Top-down:** where the senior management prescribes the requirements for a roadmap. The senior management may specify the particular format.
   - **Bottom-up ('organic'):** where the need, importance, and benefits of roadmapping are communicated and acknowledged within the organization, and the support for the application of roadmapping is provided where roadmapping can potentially address a business issue/problem.

In either case, senior management must support the process in terms of using the approach and enthusiasm. The senior management must also ensure the TRM team about resource availability (budget, time, people, and facilitation).

The roadmapping method also needs to be supported and developed if it is to be used on an ongoing widespread basis. Although simple word processing, spreadsheet, and graphics packages would help initiate the development of a roadmap, more sophisticated software would be beneficial for taking the process forward.

2.2.11. Evaluating Roadmaps for System Innovation

As a roadmap is being developed and when the final roadmap is ready to be presented, an important issue is to evaluate the roadmap. Despite all the differences in types and applications of roadmaps, there are certain clear criteria for TRM evaluation. McDowall discusses a criterion in his paper on "TRM for transition management" [62]:

- **Credibility:** is the future pathway plausible?

  The future view articulated by roadmaps must be credible and persuasive. Otherwise, roadmaps will not be able to direct and shape the behavior of the actors involved in the roadmapping process and the entire innovation system. Thus, credibility firstly demands that the roadmap is constructed on sound analysis and reasonable assumptions and methods. Secondly, the relevant expertise must take part in shaping the analysis and the roadmap. In the third place, credibility demands the involvement of actors with the greatest ability to influence the achievement of the future vision and a reasonable extent of commitment to the envisaged futures. Finally, credibility requires the adequate engagement of social, political, market, and cultural aspects of the pictured future and technological elements.

- **Desirability:** is the future pathway defensible as a good choice for society?

  When a roadmap is being developed, those developing it are responsible for articulating a desirable future pathway from a societal perspective. The questions are, who gets to decide about the future interest of society and customers? Also, the decision is made on what basis? These questions are critical, especially when the strategy is technology push rather than market pull in which there is a clearer idea about the customer's interest.

- **Utility:** does the roadmap help advance the innovation system?

  The utility factor investigates if the roadmap and roadmapping process facilitates the future development of the innovation system. While roadmaps meet the credibility and desirability criteria, they must also help provide a coherent search direction for all the innovation system actors (scientists, engineers, entrepreneurs). Also, roadmaps must develop a careful balance between picturing a confident view of a plausible and desirable future and overpromising it. Envisaging an overestimated future can damage the prospects of the innovation system [63].

- **Adaptability:** is the process consistent with reflexive, adaptive management?

  The literature on roadmaps has emphasized the effectiveness of roadmaps, where they are developed as an ongoing process rather than a one-off document). Therefore, the experts of TRM are responsible for producing and maintaining the roadmap in a reflexive manner, based on learning and evaluation and open to reflection concerning the role and value of the TRM process and its framing.

Table 2.1 provides a summary of criteria, highlighting the key questions to be addressed by each criterion:

Table 2.1. Summary table of criteria for roadmap evaluation. Adopted from W. McDowall (2012).

Criteria	Key questions
Credibility	Is the roadmap based on sound analysis?
	Does the roadmap draw on the right breadth of expertise?
	Has the roadmap secured the participation and commitment of key actors in the innovation system?
	Does the roadmap adequately address the political, social and economic aspects of the transition?
Desirability	Does the transition meet social goals established through democratic institutions?
	Does the roadmap give a clear account of the justification for the proposed pathway, with transparency in aims, process and who took part?
	Is the roadmap process inclusive and participatory?
Utility	Does the roadmap effectively articulate a path forwards that can enable alignment around common goals?
	Is the roadmapping approach appropriate for the stage of innovation system maturity?
Adaptability	Does the roadmapping process involve periodic reviews, updates and learning?
	Is the roadmapping process embedded in a broader institutional structure that enables reflexivity and learning?

Also, some important TRM success factors and barriers to success were identified in a study by Phaal et al. [64] (see Figure 2.10).

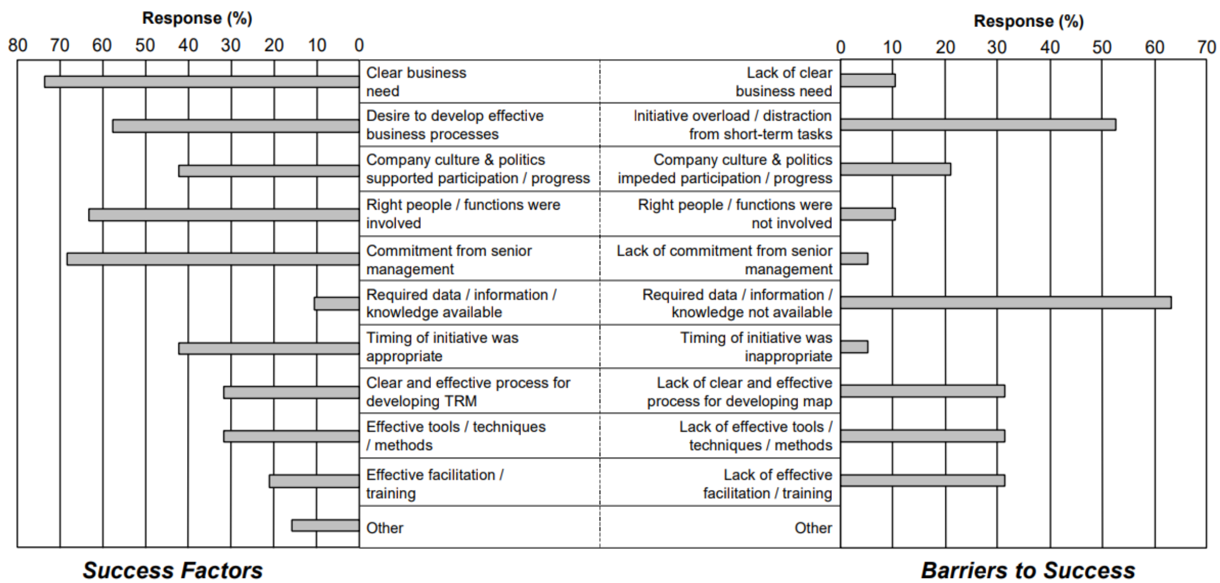


Figure 2.10. TRM success factors and barriers to success. Adopted from H. Jeffrey et al. (2013).

Moreover, Gerdsri et al. [65] discussed some of the key measures for TRM success during its 3 stages of implementation shown in Figure 2.11.

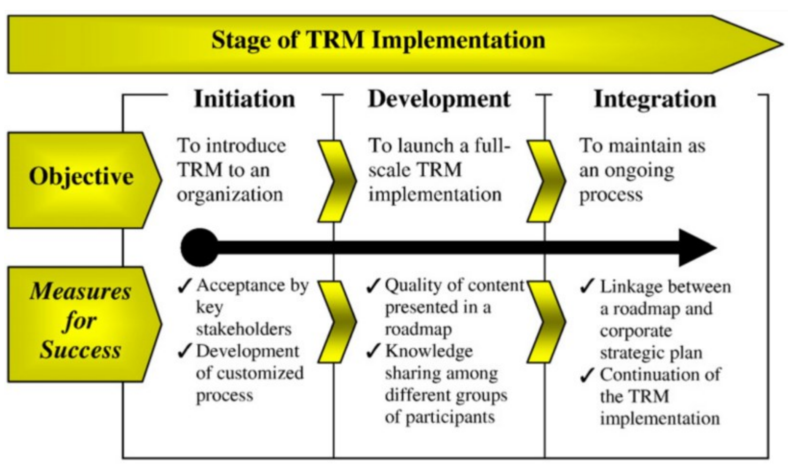


Figure 2.11. TRM objectives and measures for success. Adopted from H. Jeffrey et al. (2013).

Jeffrey et al. [66] proposed an evaluation approach for the success level of a TRM based on nine metrics, mainly focused on multi-organization TRM in which the first five metrics are single organization TRM success factors. However, metrics six to nine are firmly focused on TRM success level evaluation based on whether the TRM objectives are achieved through assessing the TRM's uptake and whether the TRM objectives have been adequately translated into actions or policies by the firm. Metric seven is focused on the level of TRM uptake based on citations and references. At the same time, metrics six, eight, and nine are instead focused on how much the TRM's recommendations have been taken into action and implemented or are being implemented across the policies, technology, and supply chain key areas of an organization. According to Jeffrey et al., metrics six to nine are mostly focused on the roadmap impact. Therefore, they will be more significant over time as they assess the results of the roadmapping process. They will also investigate whether the objectives of roadmapping have been achieved. Table 2.2 enlists the nine metrics to critically assess the success level of a TRM (more focused on multi-organization TRM).

Table 2.2. Nine metrics to critically assess the success level of a multi-organization TRM. Adopted from H. Jeffrey et al. (2013).

Type	Metric	How metric is assessed
Metrics assessing the architecture of the TRM and how it was prepared.	1. Author	Scored depending on the reputation of the author and who they selected to be a part of the TRM process (this is a traditional success factor for compiling a roadmap).
	2. Target audience	Scored based on how well the roadmap addresses its entire target audience.
	3. Roadmap message, effectiveness of delivery	Analyses a roadmap's message and how well it is delivered, taking into account format consistency and language.
	4. Are the stakeholders adequately addressed?	Measures how well, and how evenly, the stakeholders relevant to the roadmap are addressed.
	5. Ease of use — method used	Measures how easy to follow the roadmap is for readers from a range of backgrounds.
Metrics assessing the results of the TRM and whether it has achieved its objectives.	6. Status of suggested policies	Scored based on whether the roadmap's suggested policies have been implemented or are in the process of being implemented.
	7. Citations and references	Scored based on the number of times the roadmap has been cited (highest weighting for citations by another roadmap or by government).
	8. Technology	Scored based on whether the roadmap's technology recommendations have been, or are in the process of being developed.
	9. Supply chain	Scored based on whether the roadmap's supply chain recommendations have been or are in the process of being implemented.

It should be taken into account that the success factors and barriers to success for single organization roadmaps are still relevant and valuable. Therefore, having combined the success factors of single organization TRM and multi-organization TRM, H. Jeffrey et al. [66] have developed a framework of eight success factors for contemporary multi-organization TRMs, which can also be used for assessing single organization TRM to a significant extent (see Figure 2.12).

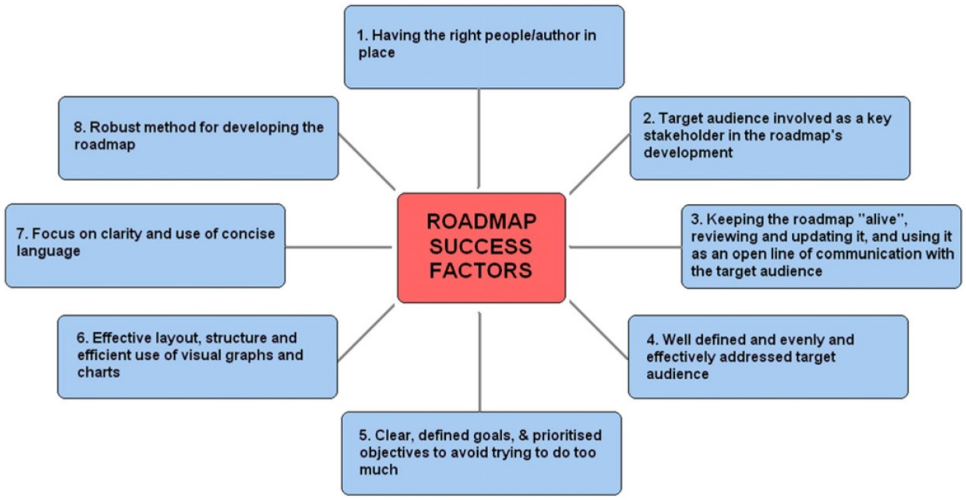


Figure 2.12. Eight success factors of multi-organization TRM. Adopted from H. Jeffrey et al. (2013).

Having the right people/author in place: Selecting the right people throughout the process is a critical factor. Involving authors with a strong reputation and experience and having input from stakeholders such as industry, academia, and government can ensure a well-balanced approach. The importance of this factor will increase as the roadmap evolves from a single organization roadmap to multi-organization and industry sector roadmaps.

Target audience involved as a key stakeholder: If the target audience of the roadmap is involved in the roadmapping process as a key stakeholder, the likelihood of acting upon the recommendations suggested by the roadmap will increase, as the target audience will feed the roadmapping team with valuable input throughout the process.

Keeping the roadmap "alive,"; reviewing and updating it, and using it as an open line of communication with the target audience: The stakeholders must be kept in regular contact through reviewing and updating the roadmaps. It can be the most important communication channel between the stakeholders and the target audience (that is advised to be a stakeholder itself).

Well-defined and evenly and effectively addressed target audience: The company implementing TRM must have a well-defined target audience. To have a successful TRM process, it is necessary to ensure that the roadmap targets all classes of stakeholders. Also, there should be a careful balance between a broad approach and a prioritized approach so that the roadmaps address all relevant stakeholders evenly and effectively.

Clear goals and prioritized objectives to avoid trying to do too much: The roadmap's goals must be clearly defined early in the process. It is also critically important for a roadmap to have prioritized objectives to avoid trying to achieve a goal without enough resources. A proper balance between properly maintaining a broad approach to evenly and effectively addressing a large stakeholder audience and prioritizing focus on important aspects of the industry (identified as presenting potential barriers) will increase the likelihood of roadmaps key recommendations being implemented.

Effective layout, structure, and efficient use of visual graphs: The roadmaps are supposed to deliver a high volume of information despite their simple appearance. Therefore, the format and approach need to be consistently clear and easy to follow.

Focus on clarity and use of concise language: The language of a roadmap must be concise while being sufficiently technical to address all technical recommendations. However, it should not be overly technical, excluding non-technical stakeholders.

A robust method for developing the roadmap: The TRM process is equally important as the resulting roadmap for many reasons: For example, information flow between different departments and stakeholders will clarify the business processes within a company or an industry sector, while new working relationships among stakeholders will form as well throughout the process. Therefore, it is crucial to select a proper roadmapping methodology that addresses all aspects of the investigated sector while integrating input from a wide range of involved stakeholders and experts from academia, industry, and government. Selecting a proper roadmapping methodology will result in a well-structured approach and addressing a full range of stakeholders.

2.2.12. Limitations of TRM

Similar to any other technique, TRM is not without its challenges. TRM's primary problem is initiating the process and robustly developing it [64]. The main reason for that is that there is little practical support available for TRM. Also, the companies applying TRM typically need to re-invent the process and adapt it to their business situation. One proposed solution for this problem is the T-plan fast start approach, as discussed in detail. T-plan is a technology management-based framework that aims to balance the technology push and the market pull [18].

A further problem discussed by Kostoff and Schaller [21] is assessing the roadmaps and the inability of the reader to determine the quality of the developed roadmap. The quality of a roadmap depends on the number of participants in developing the roadmap, the diversity of the participants' backgrounds, the competence of the experts involved in defining the forecast, and how legitimate a company adopts a vision and uses solutions from the technology roadmap [67].

Moreover, several limitations were highlighted about TRM by Strauss and Radnor [68] based on empirical-based observations they had derived from a large-scale study on the roadmapping process. Firstly, roadmapping is often considered a response to a crisis and, therefore, a one-off activity that is not part of the daily ongoing works of company management. On the contrary, to be useful, the roadmaps need to be integrated within the company's strategic management and organizational structure. Secondly, as a roadmap is a linear detail-oriented approach, the roadmap can get complex when the TRM team tries to cover details of a sudden policy change, specifically when it is about planning technological capabilities or when the company has faced an unanticipated challenge. Therefore, over-planning the details may focus the effort on making the complex manageable and make roadmapping unwieldy. Thirdly, as customers' future needs are tied with uncertainty and the company lacks an explicit assumption about it, the company may shift the focus from customer needs to the fluency of the technology. In other words, the company may unintentionally move to the technology push approach. Fourthly, critical gaps emerge in knowledge and foresight regarding future conditions and events. Finally, there must be efficient communication channels open where the roadmap is being developed; otherwise, the process will be left with gaps between the market, the product, and the technology. As a result, the roadmap will be unsuccessful within a set of time frames.

Furthermore, the TRM approach has applied chiefly to larger firms as they can provide long-term contracts and are driven by long-term planning. Therefore, TRM will suit them as a technology pull approach. SMEs, however, have not been a major executor for TRM as they are more business- rather than market-driven, can afford short-term contracts, and have less budget to invest in TRM [69].

Also, according to the study conducted by Carvalho et al. in 2013 in the literature of TRM, the limitations addressed in the related publications are listed in Appendix A, Table A.3.

2.3. TRIZ

What is TRIZ?

TRIZ is the acronym of the Russian phrase "Teorija Rezhenija Izobretatelskih Zadach," which translates to "Theory of Inventive Problem Solving" [70]. A Russian scientist and engineer (Genrich Altshuller, 1926-1998) developed the method, who studied about 400,000 technology patents and drew certain patterns. Through these patterns and regularities, he derived the process of solving problems by creating new ideas and innovation. His research led to creating a systematic process for the refinement of systems or inventing new ones. So far, more than three million patents have been analyzed by TRIZ patents to discover more patterns and propose breakthrough solutions to problems [71].

TRIZ is a human-oriented knowledge-based systematic methodology of inventive problem solving [72], and that is precisely why the proposed model integrates it with TRM. As TRM relies on expert knowledge and its primary goal is to solve a problem, a systematic methodology for problem-solving can be a great supplement for it. Souchkov similarly explains that TRIZ is based on three pillars: analytical logic, knowledge bases, and a systematic way of thinking [73]. TRIZ can provide a structure for using techniques and tools to develop a solution through a systematic approach. It provides researchers with a comprehensive toolkit with simple tools for understanding and analyzing the systems and problems. It also offers detailed techniques to develop solutions ranging from simple improvements to radical inventions which can lead to a breakthrough. Savransky also points out that as a generic problem-solving method, TRIZ works based on established principles rather than trial and error [73].

Applications of TRIZ

Traditionally, TRIZ was used in technical and engineering problems, i.e., technological processes and technical systems. However, it has recently transcended the traditional application area and is also being applied to non-technical problem areas, i.e., investment, management, and public relations [72]. Compared to the other methods applied for problem-solving, i.e., brainstorming, mind mapping, morphological analysis, TRIZ has a considerable advantage. The other methods help identify and analyze a problem and its root causes, but they are usually not capable of proposing solutions for a problem [72]. On the other hand, the systematic approach of TRIZ accelerates problem-solving in creative ways and makes sure to cover all possibilities of new solutions. It also breaks up mental inhibitors to inventive problem-solving and innovation [74].

TRIZ main techniques and tools

- 40 inventive principles for solving contradictions
- 8 trends of evolution of technical systems for identifying directions of technology development.
- 76 Standard solutions for solving system problems.
- 2500 Effects, which are concepts extracted from the body of engineering and scientific knowledge and used for inventive problem-solving.
- Function analysis and substance field analysis.
- Nine windows for understanding the context of a problem and finding solutions.
- Creativity tools for overcoming psychological inertia.
- ARIZ (the Algorithm for Inventive Problem Solving.)

The innovative solutions developed by the application of the tools mentioned above will fall into one of the following classes [72]:

- Improvement or perfection of both quality and quantity of technical systems (contradiction problems in TRIZ).
- Search for and prevention of shortcomings (diagnostics).
- Cost reduction of existing technique (trimming).
- New use of known processes and systems (analogy).
- Generation of new "mixtures" of existing elements (synthesis).
- Creation of a fundamentally new technical system to fit a new need (genesis).

How TRIZ works

On the contrary to conventional problem-solving, which goes directly from a specific factual problem to a specific factual solution, the TRIZ approach to problem-solving firstly reduces the factual, technical problem to its essentials. Instead, TRIZ states it in a conceptual or generic format. Then, it matches the conceptual problem with one of the conceptual solutions that TRIZ provides, and eventually, it translates the conceptual solution into a specific, factual solution [74]. In order to have a successful translation from a specific problem to a generic problem as well as from a generic solution to a specific solution, it is critical to ask the right questions about the key functions of the system and conduct a thorough analysis. Tools such as nine windows and function analysis can help translate the factual problems into conceptual formats and vice-versa. The TRIZ methodology provides about 100 conceptual solutions derived from the overlap of the 40 inventive principles, 8 trends of technical evolution, and the 67 standard solutions [74].

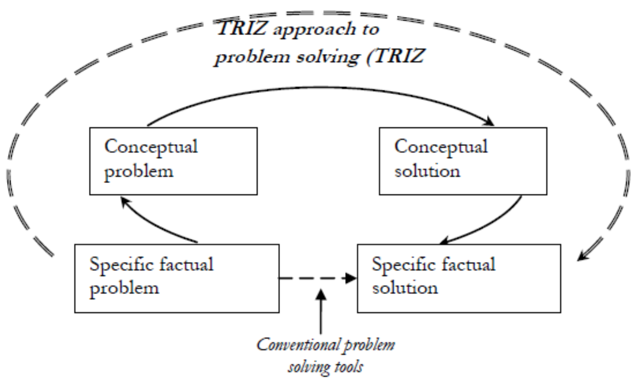


Figure 2.13. TRIZ systematic approach to problem-solving [72] [74]. Adopted from Savransky (2000) and Gadd (2011).

Five levels of invention

TRIZ can prove very effective when the difficulty level of a problem is high or when a problem requires a creative solution because the challenges are out of the ordinary. Five classifications were initially introduced by Altshuller [16]. Later, Gadd related the five levels with the source of knowledge required to solve them either within or outside the organization [74]:

Level 1: The required knowledge is available, and the problem can be solved in an obvious way.

Level 2: The required knowledge and solution must be obtained from outside the organization, but the problem can still be solved easily within the industry.

Level 3: The required knowledge and solution must be obtained from outside one industry, but it still stays within a particular discipline. Therefore, analogous thinking is necessary to inspire from proven and tested solutions in other industries.

Level 4: The knowledge and the potential solution involve different boundaries and fields. (i.e., aerospace engineering problem solved by applying knowledge from nanotechnology)

Level 5: The problem is within an undiscovered area of knowledge. It sometimes requires breakthroughs in one or multiple boundaries of science to fulfill the needs.

2.3.1. Main concepts of TRIZ

Techniques

TRIZ is founded on the systematic study of techniques and their functions. 'Technique' is a term that describes both technical systems and technological functions. These two usually supplement each other and act together [72]. All techniques have inputs, outputs, and environments. Inputs can be raw objects or materials; outputs can be products, and environments might include other techniques or humans. Moreover, inputs and outputs are in contact with the environment [72].

Figure 2.14 illustrates the techniques hierarchy. It elaborates that a technique consists of subsystems and it is a part of a super-system. The subsystems of a technique are determined based on the functions that the technique needs to deliver. However, the super system's nature depends on the problem-solvers perception of the problem context in which the technique will be used [72].

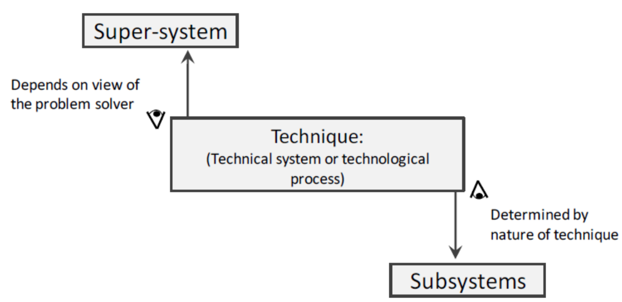


Figure 2.14. Hierarchy of technique [71]. Adopted from Ilevbare et al. (2011).

Contradiction and Ideality

Contradiction and ideality are the main two pillars of TRIZ philosophy, and at least one of these concepts is the backbone of each TRIZ problem-solving process [72] [74] [75].

According to Altshuller, there are three types of distinguished contradictions:

1. **Administrative contradiction:** This contradiction happens when an undesirable phenomenon accompanies the desired result while carrying out a process.

2. **Technical contradiction:** This contradiction occurs when a harmful function is introduced while improving a certain system function or other existing functions are negatively affected.
3. **Physical contradiction:** This arises when there are contradictory physical requirements for a system. For example, a system might need to have a large surface and low weight at the same time.

One of the TRIZ techniques is systematically removing an administrative, technical, or physical contradiction from the system.

Ideality

Every system has an ideal state which is the best possible solution for given conditions. TRIZ ideality analysis as a measure of how close a system is to its ideal state, which can be expressed as below [72] [75]:

$$Ideality = \frac{\sum Benefits}{\sum Costs + \sum Harms} = \frac{\sum UF}{\sum Inputs + \sum HF}$$

Equation 1 Ideality Equation.

In addition to solving contradiction, TRIZ also aims to maximize ideality given the conditions of the problem. It can be achieved by maximizing the benefits (useful functions, UF) and/or minimizing the costs and harms (inputs and harmful functions, HF). The ideal state of the system is also referred to as the ideal final result (IFR). A clear definition of the ideal final result of a system is a crucial step towards understanding the goals and solution requirements. It will guide the problem-solving process and eliminate the potential reworks due to improper understanding of the problem and requirements. This way, the system will also require an optimum amount of resources (inputs) for delivering the functions [72].

An explicit definition of IFR will also be beneficial when a group of stakeholders is involved in problem-solving and decision-making. Undoubtedly, there are always different views of the problem and, therefore, different goals and objectives. By having every stakeholder define his/her IFR, the group can reach a consensus and introduce a mutually acceptable solution. IFR audits can also help identify the gaps between the current solutions for a problem and an ideal solution [74].

Evolution of a technique

Technical systems and processes are evolving every day, and according to the research conducted by Atshuller, their progress generally follows certain regularities and patterns [16]. These patterns of evolution help develop innovative solutions to challenging problems and predicting the evolution of a technique in the future [75].

Savransky points out that the continuous evolution of techniques is to increase their ideality [72]. The ideality of a technique can be increased in two ways:

1. Increase of local ideality over the life span of a technique

In this type of evolution, the technique's mode of operation does not change. However, the operation parameters are improved. It will increase the useful function (the numerator of the ideality equation) and/or decrease the costs and/or harmful effects (the denominator of the ideality equation). The phases of a technique's development can be plotted against time. The result is usually an S-Curve.

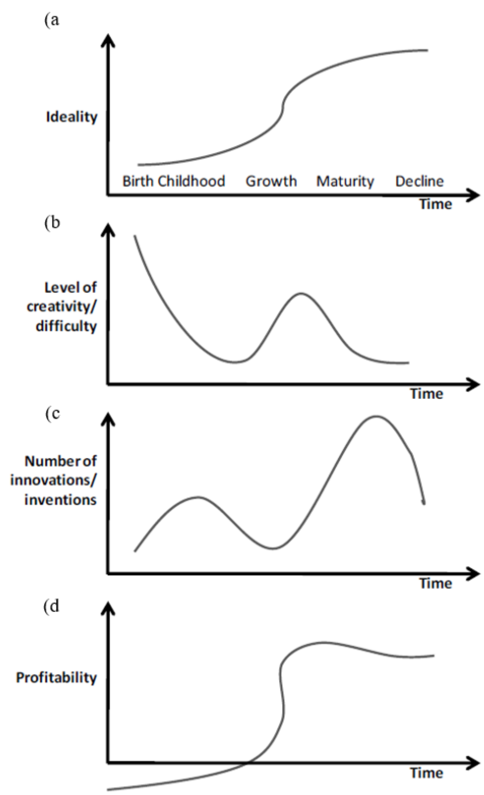


Figure 2.15. (a) Ideality against time. (b) Creativity/difficulty level against time. (c) The number of innovations/inventions against time. (d) Profitability against time. Adopted from Ilevbare et al. (2011).

Figure 2.15(a) shows that the technique reaches the limit of ideality as getting close to the end of its life span and further improvement will become increasingly difficult.

Figure 2.15(b) illustrates that an emerging technology or technique requires the highest level of creativity and has the greatest level of difficulty at the initial phases of its development. Therefore, it is no surprise that at this phase, the number of innovations and profitability are at their minimum (Figure 2.15(c)(d)).

2. Transitioning to another technique

When a technique reaches the end of its lifespan and further local improvements start to be more and more difficult, the technique can be transited to a new technique. The delivered functions of the new technique will be the same as it needs to fulfill the same system requirements; however, the functions will be delivered differently. As illustrated in Figure 2.16, the new technique either will have a higher ideality at its birth phase, or if it emerges with a lower ideality, it will have a high potential for quick improvement beyond the older technique [72] [74].

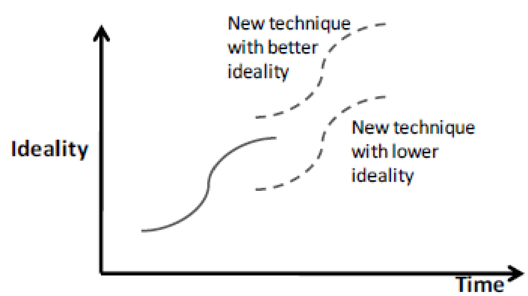


Figure 2.16. The transition of a technique [71]. Adopted from Ilevbare et al. (2011).

Gadd suggests that the development of techniques can take place through eight distinct trends:

1. Techniques tend to get more automated, and the human involvement will be lessened.
2. The development of system components will not be uniform. Some components will develop faster.
3. System evolutions follow the pattern of evolving a simple system to a complex one, and then again, the system will be simplified.

4. Systems will become more dynamic and more flexible. As a more dynamic system will require more control, the controllability of the systems will also increase.
5. System components keep getting smaller until they are so small that together they will have a field effect.
6. The effectiveness of the function delivery will increase. The systems will go beyond delivering primary benefits, and they will start to deliver all the benefits.
7. The systems will achieve more benefits while minimizing the harmful effects and costs. Therefore, the ideality will be continuously increased.
8. In the beginning phase, systems improve slowly. When getting mature, there is a rapid increase in ideality, and when approaching the end of the lifespan, the ideality reaches its limit (S-Curve).

Knowing evolution trends, we can forecast the possible paths for technique developments. Moreover, the trends give us helpful clues for problem-solving through improving the subsystems. They also provide objective views of the potentially profitable product features in the future, helping companies with market research and strategic planning [72].

Resources

One of the most important aspects of TRIZ is recognizing and mobilizing the appropriate resources for problem-solving. Gadd points out that any aspect of the system and its essential environment for providing the required features can be considered a resource. The systematic approach suggested by TRIZ for searching resources is based on understanding the functional requirements of a potential solution to a problem [74].

Savransky categorizes resources in eight categories:

- Natural or environmental resources
- System resources
- Functional resources
- Substance resources
- Energy/field resources

- Time resources

- Space resources

- Information resources

The final goal of searching the resources is to increase the technique's ideality by reducing resource harm and resource input cost. Therefore, the first step towards searching resources is to identify the beneficial resources that have harmful effects in the meantime. The next group of resources is the freely available ones, and they can be used in their existing state. However, some resources are freely available, but they are not usable in their existing state. The last group of resources is the ones that are not freely available. They must be derived from other available substances or fields which do not necessarily have the same structure or properties. Once the resources are successfully identified, a company can decide to use them or look for an alternative [72].

2.3.2 TRIZ tools

Forty inventive principles (the Contradiction Matrix and Separation Principles)

TRIZ introduces a set of 40 principles as an easy and effective tool for solving technical and physical contradictions. These principles were derived from the knowledge gathered by Altshuller by exploring the patent information of technology developments.

Depending on whether the problem involves a technical contradiction or a physical contradiction, there are two ways of using the 40 principles:

1. TRIZ introduces a contradiction matrix that can be used for addressing a technical contradiction. The matrix contains 39 technical parameters that describe the functions and features of technical systems. These parameters are arranged along the horizontal and vertical axis. Each cell of the matrix body contains the corresponding technical solution (from the 40 inventive principles) to the technical contradiction of the parameters on the crossing column and row. The parameter on the row is the improving factor, and the one on the column is the factor worsening in the result.
2. TRIZ also introduces the separation principles which are applied for understanding and solving a physical contradiction:

- Separation in time: two conflicting requirements can be in action at different times
- Separation in space: two conflicting solutions can be at different locations
- Separation in condition: two conflicting solutions can take place under different conditions
- Separation by scale: a system can be split into subsystems to have the properties of both

It is essential to understand the nature of the inconsistency in the system to identify the proper separation principle to address the physical contradiction.

Table B.1 and Figure B.1 in Appendix B illustrate the 40 inventive principles suggested by TRIZ.

Function analysis

The first step towards finding a solution for a problem is to understand the context of the problem. For that, the best way is to understand the interactions between the components of a system. Function analysis is a useful tool for this purpose. It helps to draw and clarify the system issues which are difficult to recognize. Figure 2.17 presents the symbols applied in function analysis.

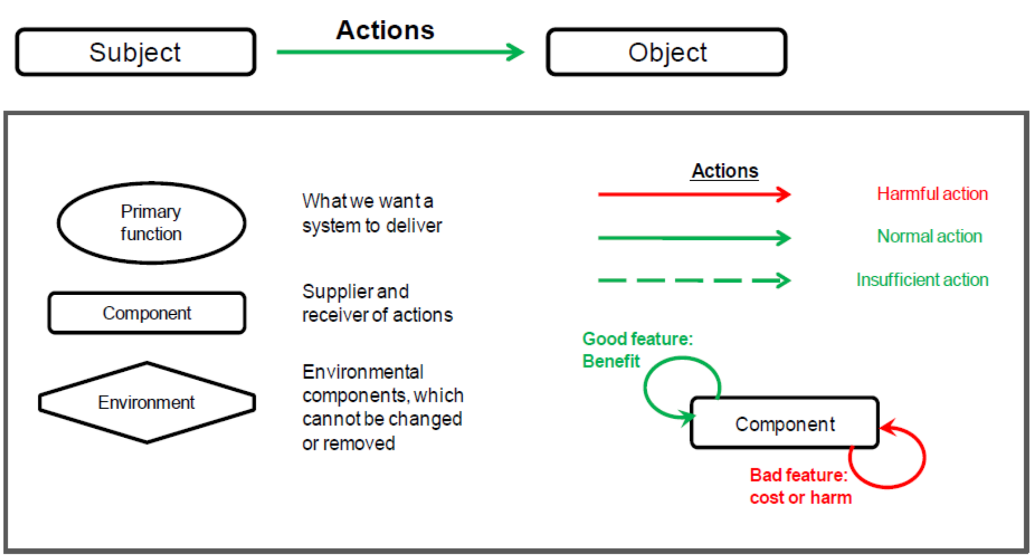


Figure 2.17. Function analysis symbols [74]. Adopted from Gadd (2011).

Function analysis starts with generating a list of all system components and their interactions. It means that the system will be broken down into simplest units. These units are in the form of subjects, actions, or objects. This representation describes the actions that a subject applies to an object in the system. The subject is the active initiator of the action or influence, and the object is the receiver of the action. The action is any kind of influence that causes changes to the object.

Substance-Field analysis

Another way to understand the system and problem is substance-field analysis (Su-Field analysis). Su-Field analysis helps the problem-solvers to exactly pointing the problems without involving unnecessary details. Su-Field uses simple triangles or arrows to map the components and interactions (see Figure 2.18).

In a Su-Field model, there are at least two substances, one acting (S_2) on another (S_1) through a field (F). Unlike the function analysis approach that usually leads to an application of the 40 inventive principles, the Su-Field analysis helps the problem-solvers to have a better understanding of the problem so they can derive a conceptual solution from the 76 standard solutions of TRIZ (the 76 standard solutions will be discussed next).

There are different generic Su-Field models depending on the nature of the problem. Figure 2.18 demonstrates different generic models along with indications of potential solutions. Within any of these Su-Field model types, a substance can be any object regardless of its complexity.

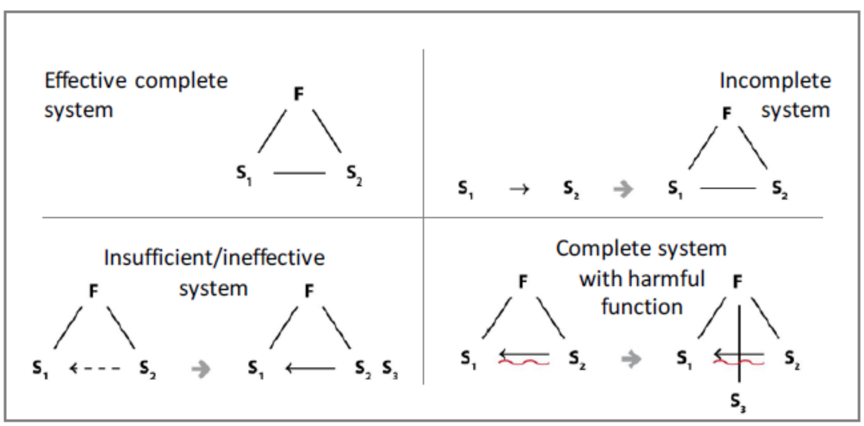


Figure 2.18. Su-Field Models. Adapted from Gadd (2011).

The incomplete system can be turned into a complete system by adding the missing component (in this case, the field). An insufficient or ineffective system can become a sufficient or effective system by transforming the insufficient interaction effective (in this case by adding a third substance). Moreover, a complete system with harmful functions can transform into an effective system by blocking the harmful effect (in this case, by adding a third substance).

TRIZ standard solutions

TRIZ introduces 76 standard solutions for engineering problems. These standard solutions are classified into five groups according to the nature of the problem.

- Improving the system with no or little change (13 standard solutions)

    It can happen through improving the performance of an inadequate system or eliminating or neutralizing the harmful effects of the system.

- Improving the system by changing the system (23 standard solutions)

    Minor system modifications can be introduced to improve the efficiency of an engineering system.

- System transitions (6 standard solutions)

    Generally, system transition happens through combining the system with other elements or systems. Therefore, these changes are beyond minor modifications and can potentially develop solutions at a different level.

- Detection and measurement (17 standard solutions)

    This class of solutions either focuses on measuring a copy of the parameter instead of the actual one in the system or eliminates the need for measuring or detection in the system.

- Strategies for simplification and improvement (17 standard solutions)

    The solutions in class 5 are methods for simplifying the system while increasing the ideality. Class 5 solutions can be used to simplify the solutions derived from the other classes of standard solutions.

The TRIZ 76 standard solutions can be seen in Appendix C.

Nine windows

This tool, made of nine cells in the form of a 3x3 matrix, is a helpful technique for understanding the context of a problem. As shown in Figure 2.19, the nine windows tool, the x-axis focuses on the time. It illustrates the history of the problem as well as its present state and its forecasted future. On the other hand, the y-axis focuses on the hierarchy of systems and further details. It categorizes the systems involved into the system, subsystem, and super-system. Mapping a system with "nine windows" helps us have better clarity about the path of the system from its past to its future. It also provides possibilities for action to increase the ideality when the expected future of the system is understood.

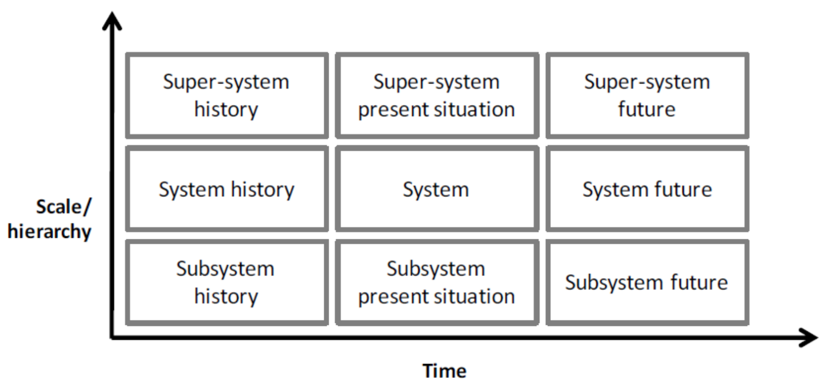


Figure 2.19 Nine windows. Adapted from Gadd (2011).

Additional TRIZ tools can be found in Appendix B.

2.3.3. General process of TRIZ

The following four-step process can be followed to solve a problem based on TRIZ:

1. The problem needs to be identified. To identify the problem, the system, its current state, and ideal state, and the environment must be properly defined.
   TRIZ tools that can be helpful for this stage are: pattern of evolution, ideal final result, nine windows
2. The specific problem will be translated into a generic conceptual problem.

TRIZ tools that can be helpful for this stage are: ideal final result, function analysis, Su-Field analysis

3. A conceptual solution can be developed using TRIZ tools such as contradiction matrix, inventive principles, and separation principles
4. The conceptual solution will be translated into a set of actual and specific solution options. Finally, one of the solutions will be selected using feasibility studies and/or multi-criteria decision-making methods.

Figure 2.20 illustrates the TRIZ problem-solving process.

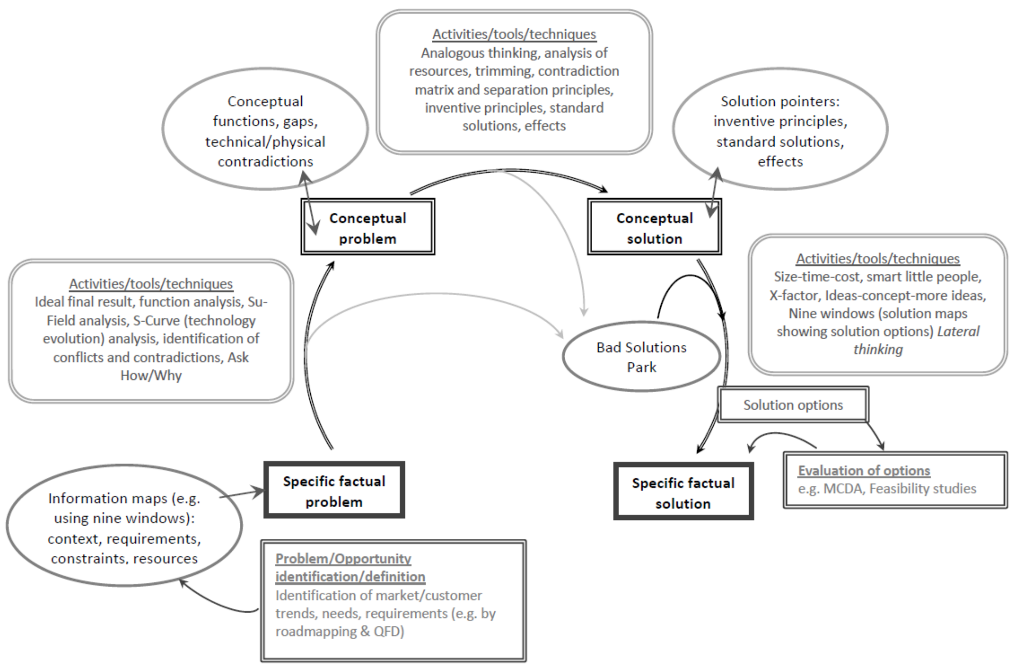


Figure 2.20 TRIZ process. Adopted from Ilevbare et al. (2011).

2.3.4. Integration of TRM and TRIZ

The literature shows that there have been some efforts in integrating the two methods of TRM and TRIZ. Shuch & Grawatsch presented a TRIZ based technology intelligence framework [6]. Different TRIZ tools such as the evolution trends have been incorporated in the technology intelligence method in their approach. The process gives valuable insights to a technology owner about the potential of different technologies that deliver the same primary function.

Another effort toward this combination was the TRIZ based roadmapping process outlined by Moehrle et al. [76]. Their approach was not very different from Shuch & Grawatsch's [6] process. The goal of their process was to use the evolution trends for forecasting future technologies and improving the market share by gaining product and service ideas.

Norrie focused on defining major technology areas for achieving the critical system requirements [77]. He also worked on exploring alternatives and timelines for which he adopted different TRIZ concepts such as contradiction. In his research, he pointed out how TRIZ can supplement the roadmapping process [77].

Lee [78] and Zhang et al. [13] suggested the incorporation of TRIZ into the T-plan approach for roadmapping proposed by Phaal et al. [5]. Lee, particularly the S-Curve analysis, can give valuable insight into the maturity of technology alternatives. At the same time, Zhang et al. suggested that the evolution trends can help the roadmapping team with more structured decision-making [79] [13].

Ilevbare et al. proposed a model for applying TRIZ to enhance the TRM process [71]. They focused on the main three pivotal stages that are common between TRM and TRIZ:

1. Proper understanding of the current state of the system
2. Proper understanding of the intended future state of the system (Ideal Final Result)
3. The transformation between the current state and the intended future state

They suggest that TRIZ techniques can address the aspects of TRM that focus on the mentioned stages. Different sets of TRIZ techniques can be directly used to provide a proper understanding of the problem or the current state of the system and the intended future state. Moreover, TRIZ can enhance the process of problem-solving for the transition to the future state.

Figure 2.21 demonstrates different tools of TRIZ that can be used in different stages of roadmapping.

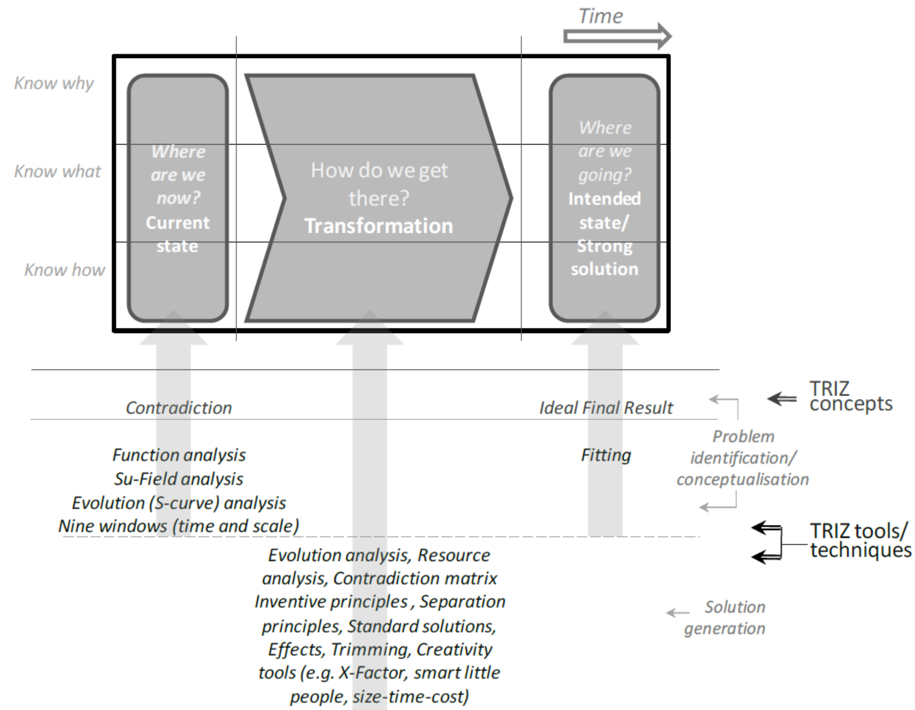


Figure 2.21 Generic roadmapping framework overlaid with the generic TRIZ process. Adopted from Ilevbare et al. (2011).

Taking a closer look, we can see how TRIZ concepts and tools can be incorporated into the TRM process. Figure 2.22 illustrates how a T-plan roadmapping process can benefit from TRIZ.

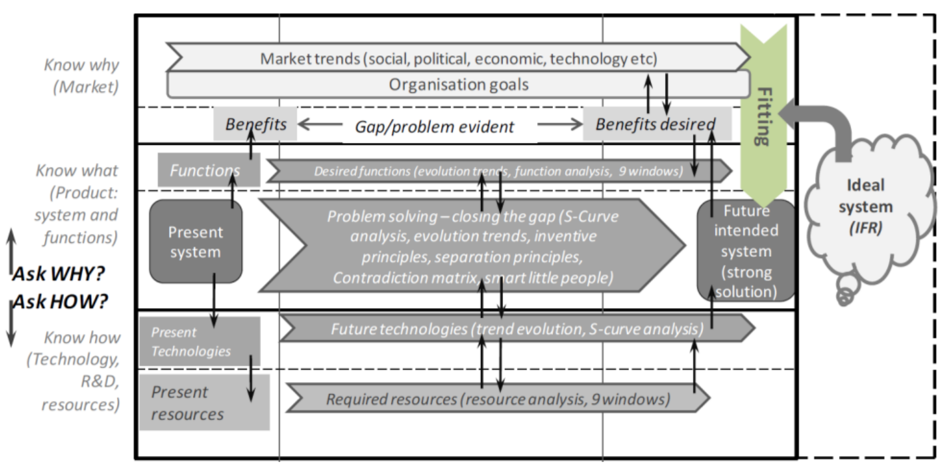


Figure 2.22 Illustration of the application of TRIZ concepts in TRM. Adopted from Ilevbare et al. (2011).

2.4. Risk management and Bayesian Belief Network

Because of unpredictable and uncertain events, the actual problem is different from the hypothesized scenarios [68]. The concept of risk was initially defined fundamentally based on probability. It was defined as the uncertainty expressed under the rules of probability calculus [80]. Later, its definition expanded to include expected value, consequence, and the impact of uncertainties on objectives [80]. However, risk is commonly considered a three-factor concept. As discussed by Kaplan and Garrick, risk can be expressed as a triplet of a scenario, the probability of the scenario, and the consequences of the scenario [81]. Scenarios are the future events that affect the process of technology planning and development. Therefore, their consequence and impact need to be quantitatively measured. This research follows Kaplen and Garrick's definition and supplements it with an approach for measuring the severity of the consequence.

There are different approaches and methodologies for risk management. For example, Wang et al. proposed a system dynamics approach for risk management [82]. Gailis et al. suggested scenario trees [83]. Islam et al. adopted a fault tree analysis [84]. Furthermore, Abaei et al. [85], Kruger & Lake [86], Khakzad et al. [87], Khakzad [88], and Yet et al. [89] all proposed methods with Bayesian network. Among the mentioned approaches, Bayesian networks have proven to be powerful tools for probabilistic inference, especially in complex domains with a large number of variables [90]. That is why there are used in many domains for risk and safety analysis based on probabilistic and uncertain knowledge.

Bayesian Networks (BN) is a probabilistic graphical model that represents the relationships between and conditional probability distribution among variables [91] [92]. A Bayesian network consists of a set of nodes representing variables and a set of arcs representing the dependencies between linked nodes. The child node is dependent on its parent node while being conditionally independent of others. The Bayesian network can update the prior occurrence probability of events, given new information based on Bayes's theorem. The given new information is usually the result of occurrence or non-occurrence of accidents or primary events during a process's operational life. The belief of uncertainty of an event or a hypothesis is assumed provisional, called prior probability $P(H)$. This prior probability will be updated as soon as new evidence E is available. The new evidence provides a revised belief about the uncertainty of the event or hypothesis H. The new probability is called posterior probability $P(H \mid E)$. As demonstrated by equations 1 and 2, the conditional probability P(A | B) shows how the availability of new evidence can influence the probability distribution of a dependent node.

$$P\ (A \mid B) = \frac{P\ (A \cap B)}{P(B)}$$

Equation 2 Conditional probability

$$P\ (A \mid B) = \frac{P(B \mid A) * P(A)}{P(B \mid A) * P(A) + \ P(B \mid \bar{A}) * P(\bar{A})}$$

Equation 3 Conditional probability equation expanded based on the Bayes's theorem and the low of total probability

2.4.1. TRM and uncertainty

The literature shows that there have been some efforts to reflect the uncertainty and complexity of the environment in TRM. Amer et al. [93], Firat et al. [94], Geum et al. [95], Hansen et al. [96], Lee et al. [78], and Siebelink et al. [97] applied scenario planning to cope with uncertainty and to obtain robust roadmap. They had a reflecting proactive viewpoint, describing logical sequences of events to explore the probable future evolving from past and present.

Ilevbare et al. [71] worked on risk-aware TRM, which embedded roadmapping with risk management procedures. His method involved retrospective studies in understanding the past events through semi-structured interviews. Therefore, the method relied on subjective opinions and did not propose a definite process to alight risk management with TRM.

2.4.2. Bayesian Network

Jeong et al. [98] suggested developing a risk-adaptive technology roadmap using a Bayesian network. Their method worked by reacting to the occurrence of risk events and adapting to possible consequences caused by risk. Therefore, it made the decision-makers plan adaptively for changing environments. To minimize the cost of roadmapping, they conducted a text mining approach on bibliographic data of the domain instead of an expert-based study. They transformed the TRM elements into a Bayesian network node and investigated the relationships and how the risk events could affect the TRM elements (see Figure 2.23). They also could see the impact of the availability of new evidence (i.e., knowing that a risk event happens) on the posterior probabilities of the nodes.

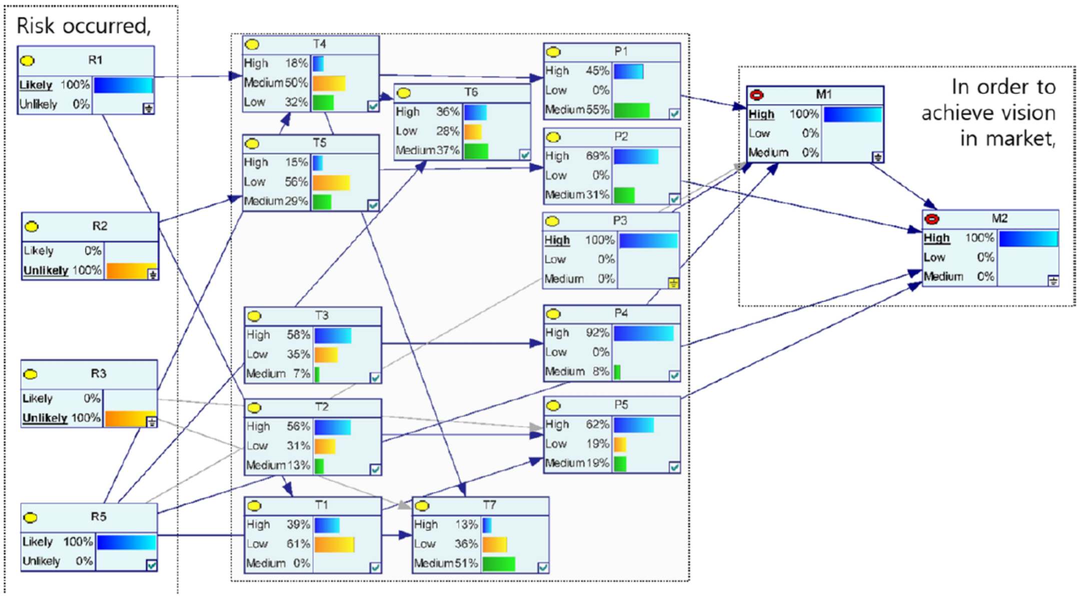


Figure 2.23 The Bayesian network for new technology roadmap with risk events [98]. Adopted from Jeong et al. (2021).

In a Bayesian network, the connections and dependencies can get complicated. However, the dependencies can be categorized into two general types. Either multiple nodes influence a dependent node, or one node influences multiple dependent nodes. A combination of these two typical types can create large networks. Equation 4 demonstrates the situation in which more than one parent nodes have the same child node (see Figure 2.24(a)):

$$P(\mathrm{X1} \mid Y) = \frac{\{P(Y \mid X1, X2)\,.\,P(X1)\,.\,P(X2) + P(Y \mid X1, \overline{X2})\,.\,P(X1)\,.\,P(\overline{X2})\}}{\{P(Y \mid X1, X2)\,.\; P(X1)\,.\; P(X2) + P(Y \mid X1, \overline{X2})\,.\,P(X1)\,.\,P(\overline{X2}) + P(Y \mid \overline{X1}, X2)\,.\,P(\overline{X1})\,.\,P(X2) + P(Y \mid \overline{X1}, \overline{X2})\,.\,P(\overline{X1})\,.\,P(\overline{X2})\}}$$

Equation 4 Conditional probability of each of multiple parents

Equation 4 can be written in a more general way if the aggregated conditional probabilities (i.e., p(Y | X1) instead of p(Y | X1, X2) are given (see Equation 5):

$$p(X_i \mid Y) = \frac{p(Y \mid X_i)\,.\; p(X_i)}{\sum_{j=1}^{n} p(Y \mid X_j)\,.\; p(X_j)}$$

Equation 5 General presentation of equation 4

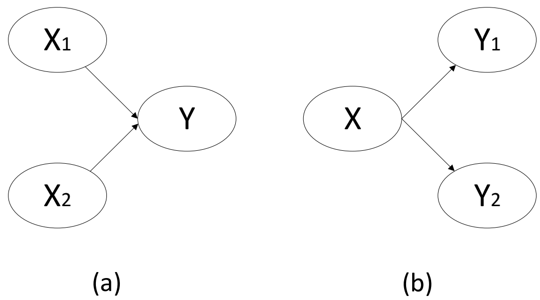


Figure 2.24 Structure cases in Bayesian Network

Equation 6 demonstrates the situation in which one parent node has more than one child node (see Figure 2.24(b)):

$$p(X|\, Y_i) = \frac{p(Y_i \mid X)\ .\ p(X)}{p(Y_i \mid X)\ .\ p(X) + p(Y_i \mid \bar{X})\ .\ p(\bar{X})}$$

Equation 6 Conditional probability of a parent node with multiple child nodes

An important downside of Jeong et al.'s risk-adaptive approach is that they do not investigate the importance of each node or each node's contribution in meeting the market demands. Therefore, while adapting to risks (i.e., replacing a technology with an alternative in case a risk event significantly influences it), they cannot guarantee that the replaced technology has the same importance in or contribution towards the roadmap's goal. In the proposed framework in this research, this issue has been addressed by weighting the nodes through incorporating an ANP analysis.

2.5. Analytic Network Process

Analytic network process (ANP) is a multi-criteria decision analysis method [99]. The ANP is the generalization of the Analytic Hierarchy Process (AHP) introduced by Thomas L. Saaty in 1980 [100]. Like AHP, ANP also uses paired comparisons to derive normalized absolute scales of numbers to prioritize the network nodes. However, unlike the AHP, the ANP involves a network of dependence and feedback between all the factors and criteria. As a result, the ANP allows the decision-makers to input judgments and measurements to prioritize the influence of the factors and clusters of factors in decision [101]. Therefore, this method has been used as a suitable tool for evaluating alternative decisions in the design and planning process in many domains.

2.5.1. ANP procedure

As a problem may consist of multiple subproblems, an Analytic Network Model may also be a single network or a group of subnetworks to represent a problem. A network consists of clusters (i.e., groups of elements), nodes (problem variables, attributes, or alternatives), and arcs (the connection between elements). Thus, an ANP can be created through three main steps:

a) Selecting and grouping logical nodes and clusters to describe the problem in the best way possible
b) Examining the influences and creating the connections in the model
c) Pair-wise comparison between the nodes and clusters

After the pair-wise comparisons, the ANP algorithm calculates the best alternative for the problem through supermatrices. The ANP associates three supermatrixes with each network in which each component is defined as a block with corresponding rows and columns with cluster names:

1. Unweighted Supermatrix: This matrix derives the local priorities from the pair-wise comparisons in the network
2. Weighted Supermatrix: This matrix is the result of multiplying all the elements of a component of the unweighted supermatrix by their cluster weight
3. Limit Supermatrix: This matrix is obtained by raising the weighted supermatrix to powers by multiplying it by itself. The matrix will reach its limit, and the multiplication process will stop when all the columns are the same and contain the same numbers. As the limit matrix is reached, the priorities can be read from any column simply because all the columns are identical.

2.5.2. Integration of BN and ANP

Szucs & Sallai proposed an approach for joining the analytic network process and Bayesian network model for fault spreading problems [102]. They focused on the probabilistic approach of fault trees in info-communication networks, where certain types of faults occur in the inner part of the network, and their influence spreads throughout the dependent nodes all the way to the front end.

In their research, they introduced vectors $W_i = [W_{i1}, W_{i2}, \ldots, W_{im}]$ to represent the weight of different effects on each N_i node (m is the number of the nodes without children). In this so-called Vectorized Bayesian Network, the nodes not only contain probabilities, but they also have a weight vector corresponding to any information, i.e., effect, impact, importance, cost). The weight vectors at nodes with no children (leaves) are given, and the weight vectors of the parents should be determined. Also, the dimension of the vector does not change from child to parent and is always equal to the number of leaves. In the case of Figure 2.24(a), the weight vector of X_1 is $W_1 = [W_{11}, W_{12}, \ldots, W_{1m}]$. In situations such as Figure 2.24(a) where there are multiple parent nodes and only one child, the ratio of the weight vector of a parent node is the conditional probability (see eq. 7):

$$W_{1k} = P(\mathrm{X1} \mid Y) \,.\, W_k$$
$$= \frac{W_k \,.\, \{P(Y \mid X1, X2) \,.\, P(X1) \,.\, P(X2) + P(Y \mid X1, \overline{X2}) \,.\, P(X1) \,.\, P(\overline{X2})\}}{\{P(Y \mid X1, X2) \,.\, P(X1) \,.\, P(X2) + P(Y \mid X1, \overline{X2}) \,.\, P(X1) \,.\, P(\overline{X2}) + P(Y \mid \overline{X1}, X2) \,.\, P(\overline{X1}) \,.\, P(X2) + P(Y \mid \overline{X1}, \overline{X2}) \,.\, P(\overline{X1}) \,.\, P(\overline{X2})\}}$$

Equation 7 Weight vector of each child node based on the parent node

For every $1 \leq k \leq m$. The weight vector can be calculated in a similar way for the other parent nodes.

For a situation such as Figure 2.24(b) where there is one parent node, and multiple child nodes, the weight vector of the parent node is cumulated from the weight vectors of its child nodes (see eq. 8):

$$W_k = \sum_{i=1}^{n} p(X \mid Y_i) \,.\, W_{ki} = \sum_{i=1}^{n} \frac{p(Y_i \mid X) \,.\, p(X)}{p(Y_i \mid X) \,.\, p(X) + p(Y_i \mid \bar{X}) \,.\, p(\bar{X})} \,.\, W_{ki}$$

Equation 8 Weight vector of parent node based on the children.

For every $1 \leq k \leq m$.

Chapter 3

Conceptual Framework

The conceptual framework chapter explains how a thorough risk-adaptive TRIZ-based TRM process has been developed, adopting and enhancing the methods discussed in the literature review section. This section recaps the key concepts of the domain and the literature's corresponding methods and provides critical analysis. In addition, it presents the steps of the framework developed in this research. Figure 3.1 provides a visual illustration of the developed framework.

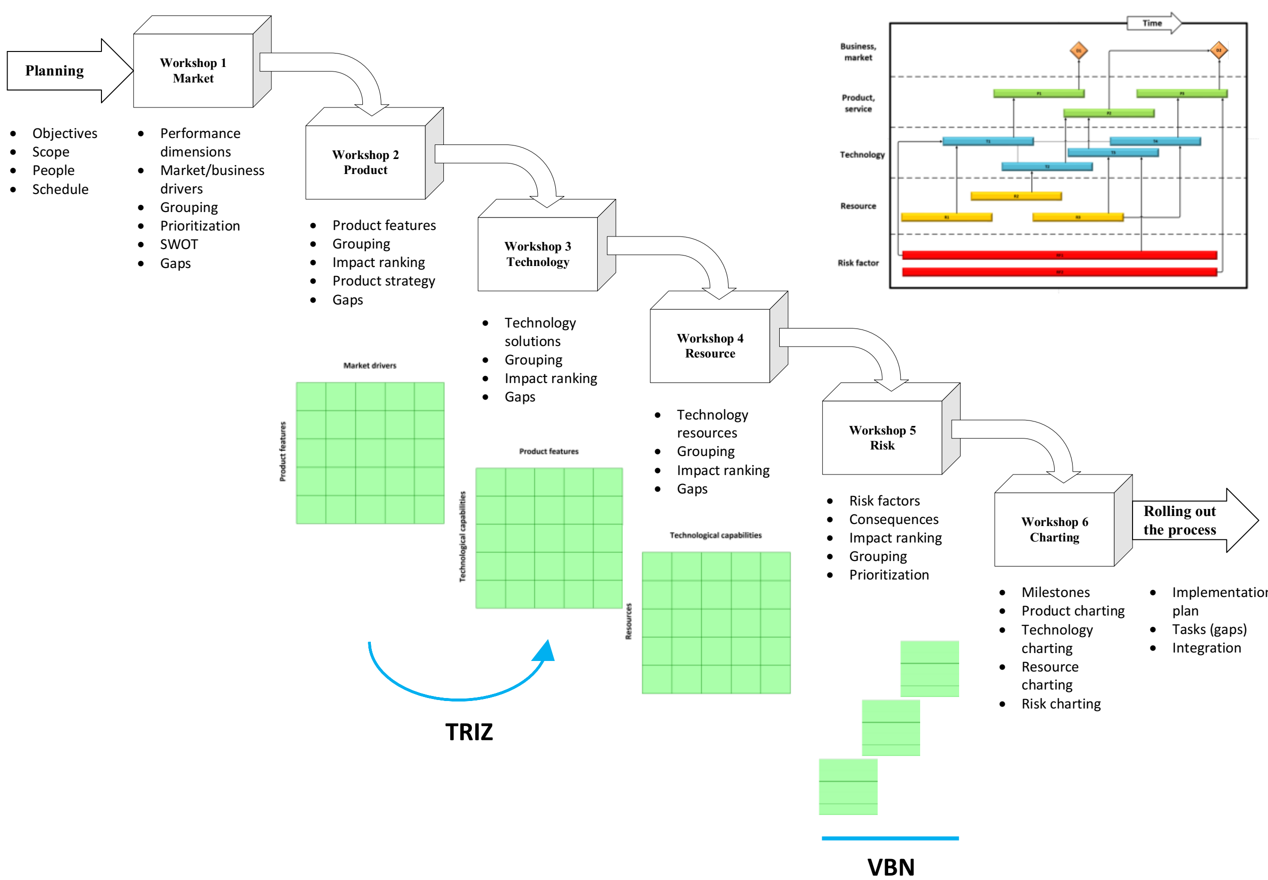


Figure 3. 1 Enhanced T-plan for new technology development strategic planning

3.1. TRM initiatives (enhanced T-plan and five-layer roadmap)

Among the different approaches for initiating the process of TRM, this framework adopts the T-plan fast-start approach as a flexible yet structured approach for rapid initiation of roadmapping. The T-Plan is focused on product-TRM and is designed to be agile, flexible, rapid, efficient, and scalable [7]. It uses four multi-functional and potentially multi-organizational workshops. In these workshops, different aspects of the roadmap will be investigated, and inputs and outputs of the roadmapping activity will be linked to strategic milestones. However, the traditional T-plan does not have a framework for investigating the technology resources and risks. These two factors become critical when the technological capability required to develop a product feature to respond to a market driver is not yet developed. In other words, a state-of-the-art technology needs to be developed to meet the roadmap requirements. In this case, coming up with a technological solution in roadmapping is much more complicated than when the technological capabilities are available. Therefore, in such a situation, the roadmapping team needs to investigate the resources in the form of research and development in different science domains, engineering fields, or industry sectors that can advance and potentially develop a better technological capability. Alternatively, in a better scenario, they could have a breakthrough and shift the entire S-carve of ideality upwards and start a new technology generation. When dealing with state-of-the-art technology developments and potential breakthroughs, multiple positive or negative risk factors must be considered. Therefore, the roadmapping team needs to dedicate a sufficient amount of time to go through the risk aspects of the process. As a result, two layers corresponding to the resources and risks will be added to the roadmap.

This research proposes an enhanced T-plan in which additional workshops focus on resources and risks. The enhanced T-plan process consists of six workshops from which the first five focus on the five layers of the roadmap respectively, and the last workshop focuses on charting the final draft of the roadmap:

Enhanced T-plan workshops focus:

1) **Market:** this workshop focuses on business/market drivers identification, categorization, and prioritization. Furthermore, the critical market gaps are identified during this workshop.

2) **Product:** this workshop focuses on the product features corresponding to the market drivers. In this workshop, potential products' features, attributes, and functions are identified and prioritized based on their influence on the market drivers.
3) **Technology:** in this workshop, the potential technological capabilities to address the product features are identified and prioritized. An essential part of this workshop is identifying the critical technology gaps between the current technologies and the required technologies not yet developed.
4) **Resources:** This workshop focuses on the necessary supporting resources in the form of research and development to address future technological capabilities. The resources can be categorized and prioritized depending on their potential chance of advancement and breakthrough.
5) **Risks:** this workshop investigates the risk factors of new technology development. In this workshop, risk factors corresponding to different roadmap elements are identified and prioritized based on their probability, consequence, and impact.
6) **Charting:** in this workshop, the initial roadmap is developed based on the output of the previous five workshops. The developed roadmap will link the market drivers, product features, technology perspectives, resources, and risks and let the participants make corresponding decisions and agree on actions.

At the beginning of each workshop, the drivers of the previous layer discussed in the last workshop must be translated to the drivers of the new layer. This important task is done by analysis grids (or QFD method) to associate the upper-level drivers to the current-level drivers. Therefore, at the beginning of the second workshop, the market drivers will be translated to product features. At the beginning of the third workshop, the product features will be translated to technological capabilities. Furthermore, at the beginning of the fourth workshop, the technological capabilities will be associated with related resources. As risks can be associated with the elements of all layers, the risks will require multiple association analysis grids.

3.2. Supplementing the enhanced T-plan with TRIZ

This framework incorporates TRIZ techniques into the T-plan fast-start approach, as Ilevbare et al. [71] suggested. As demonstrated in Fig 2.30, different techniques of TRIZ can be used in different stages of TRM. Table 3.1. summarizes the TRIZ techniques that can be taken advantage of in different stages of roadmapping.

Table 3.1 Classification of TRIZ tools according to application field [71]. Adapted from Pannenbacker (2011) through Ilevbare et al. (2011).

Application field	***Concept / tool / technique***	***Mode of application***
Current state	Function (and object) analysis	Modeling the system and components, as well as positive and negative functions and interactions
	Contradiction	Confronting desired functions with harmful effects
	Su-Field analysis	Modeling the substances and fields of the system and analyzing the problem
	Evolution analysis	Analyzing the previous evolution of the system
Resource analysis	Resource analysis (system analysis, substance field analysis, and performing a systematic search for resources)	Identifying the available resources in and around the system
Goals	Ideal Final Result (IFR)	Identifying the ideal solution
	Fitting	Consideration of restricting conditions to the ideal
Intended state	Strong solution (or the ideal outcome achievable	Balancing between the IFR and fitting
Transformation	Inventive principles	Direct application of inventive principles
	Contradiction matrix (and inventive principles)	Resolving conflicting benefits and harms
	Separation principles	Separating conflicting system requirements
	Su-Fields analysis	Application of standard solutions
	Evolution analysis	Anticipating the potential future developments of the system
	Resource analysis	Applying available resources
	Effects	Making use of scientific and engineering knowledge from different disciplines

3.3. Risk analysis of TRIZ-based technology roadmap

An important attribute of the TRIZ-based technology roadmap proposed in this research is that the technology perspectives are probabilistic. The reason is that these technology capabilities are mostly not yet developed, and they associate with different aspects of risk. As suggested by Jeong et al. [98], the Bayesian network is a powerful tool for probabilistic inference in complex systems. Therefore, this framework also uses the Bayesian network as the primary tool for technology development risk analysis.

Jeong et al. founded their research on bibliographic data and text mining and evaluated probabilities and influences based on text mining outputs. In the context of state-of-the-art technologies, however, this approach is not very practical because the data and literature on the subject either are limited or they are not available due to information confidentiality by pioneer companies. Therefore, unlike Jeong et al.'s approach, this framework derives the probabilities and dependencies of the network from expert opinions and lab tests. However, the procedure of evaluating the probabilities is not within the scope of this research.

Despite few similarities, the application of the Bayesian network for risk analysis in this framework is entirely different from the one suggested by Jeong et al. Like the Jeong et al. method, this framework suggests that risks can influence the technology and product nodes directly or indirectly throughout the roadmap. However, unlike the Jeong et al. approach, this platform suggests that the risks can also influence the resource and market nodes. Therefore, risk factors can be associated with resources, technology capabilities, product features, and market drivers. It can be concluded that depending on the area of concentration of risks influences, different layers of the roadmap can be engaged with uncertainty. If the risks are concentrated in the top layer, we can conclude an uncertain market/business environment. On the contrary, if the risks are concentrated on the bottom layers, we understand that the roadmap deals with uncertain technology capabilities. Observing many risk factors associated with the product layer of the roadmap might mean that the project requires a better R&D unit to translate the technological capabilities to product features more effectively.

Figure 3.2 illustrates a situation in which the risks are associated with the resource and technology layers. In such situations, the behavior of the market is not subject to many questions. These circumstances can occur when an industry requires some product features while the technology for addressing them is not fully developed yet. Therefore, the market desires those features. Thus, not many risk factors are associated with the market layer. However, as the technology is at its birth phase of the S-carve, the uncertainties associated with the resource and technology layers are significant.

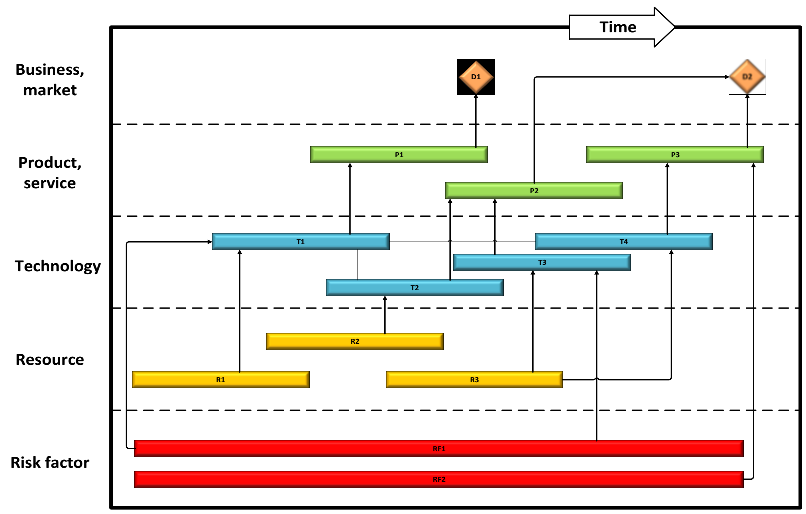


Figure 3.2 Roadmap for new technology development with resource technology uncertainty.

Figure 3.3 illustrates the situation in which the risk factors are influencing the market drivers. This situation means that the roadmap deals with an uncertain market environment. These circumstances usually occur when the required technology is not a struggle, and it already exists (in this case, the resource layer can be unnecessary as there will not be any technological advancement requiring significant R&D resources). The problem is to know what the market is pulling. This matter, however, will not be straightforward in fluctuating markets in which the trends and demands are changing rapidly under the influence of a large number of factors. In such roadmap, the risk layer can be illustrated at the top to avoid the crowdedness caused by long arrows.

Risks factors may be associated with both bottom layers and top layers at once. In that case, we will be dealing with a tremendous amount of uncertainty throughout the roadmap where neither the market is certain nor how we want to respond to its demands.

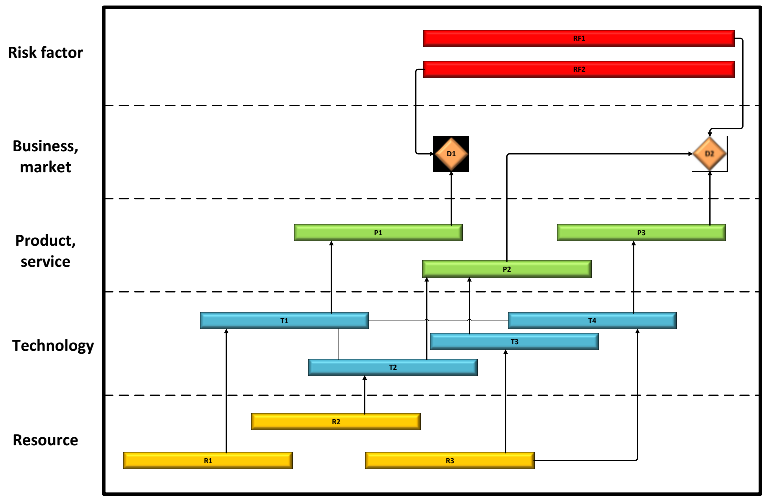


Figure 3.3 Roadmap for new product features with market/business uncertainty.

3.4. Risk identification and assessment

This framework considers risk as all events with a considerable possibility of negatively or positively impacting the future. It categorizes them into two groups: intrinsic and non-intrinsic risks. The intrinsic risks are the ones associated with the nature of new technology development. For instance, every developing technology can fail. Alternatively, technology development might start to require more resources (i.e., financial, R&D, resources) than prior estimation, which can lead to delays in the process. The non-intrinsic risks are the ones outside of the system and usually environmental. For example, a new regulation by a government can completely rule out the use of a particular material in the technological solution. Alternatively, in the case of market risks, if being first to the market is a weighty market driver, a potential competitor can be considered a risk to this market driver. On in contrary, as a positive risk, a new regulation can open up new options and opportunities for technology development.

Intrinsic risks

Regardless of the industry or the technology, developing a new technique or solution is always bound with intrinsic risks. In addition to the technologies, these risks can directly influence the product features. In this framework, the intrinsic risks are embedded into the technology and product nodes by discriminating the probability of each node into three states:

1) **Successful:** the probability of development of the node within the desired timeframe
2) **Late:** the probability of development of the node after the desired timeframe
3) **Failed:** the probability of the node's failure

These probabilities will be derived from experts' knowledge or literature if available.

Figure 3.4 illustrates how a technology capability and product feature looks like in a Bayesian network:

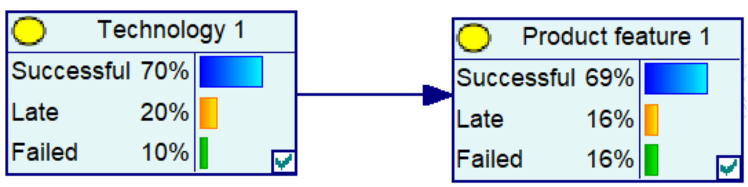


Figure 3.4 Technology capability and product feature nodes in a Bayesian Network.

The figure illustrates the three probability states and the corresponding probabilities for each node.

Non-intrinsic risks

There are different domains of non-intrinsic risks to which a roadmap can be exposed. Non-intrinsic risks can be environmental, such as climate change and its restrictions on the technology development process. Another domain of non-intrinsic risks is compliance and legal violations. In another aspect, the reputation of a company in case of technology failure can be damaged. This matter can be considered a reputational risk. On the other hand, a positive risk impacting the roadmap can be a breakthrough in one of the multiple R&D resources that can lead to significant technology advancement or the birth of new technology. Therefore, non-intrinsic risks will appear as individual nodes on the Bayesian Network and can influence multiple nodes in different layers of the roadmap. The non-intrinsic risks must be identified by the experts of different domains involved in the roadmapping process. Figure 3.5 illustrates how a non-intrinsic risk node looks like in a Bayesian Network.

The probability states of a risk factor are simply either happening or not (Yes/No).

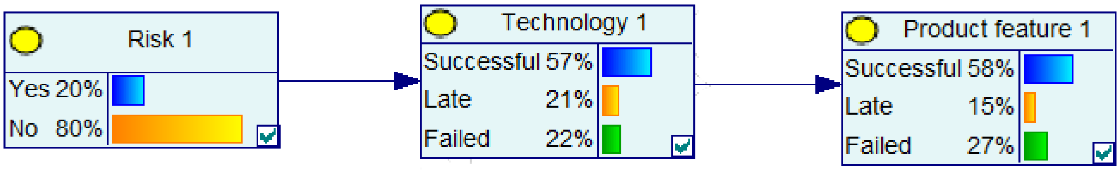


Figure 3.5 Risk, Technology, and product feature nodes on a Bayesian Network

The connections between Bayesian Network nodes are identified based on the association analysis grids developed in T-plan workshops, and the probability distributions are derived from expert opinions (see Table 3.2).

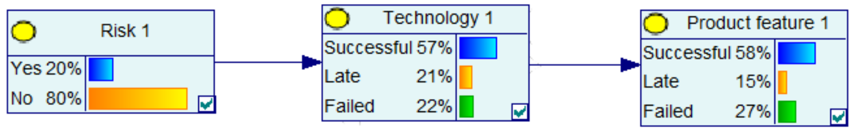
Table 3.2 Conditional probability of Product feature 1, given an evidence about Technology capability 1.

Technology 1	Successful	Late	Failed
Successful	0.9	0.3	0
Late	0.05	0.6	0
Failed	0.05	0.1	1

3.5. Incorporating Bayesian Network

Bayesian Network is a powerful complex system probabilistic inference because it can update the probabilities of all the nodes on the system if new evidence becomes available. It means that the network probabilities will be updated, given a new piece of information -evidence- (i.e., the occurrence of a risk event). Therefore, multiple scenarios can be simulated, and the behavior of the model can be observed. For example, given the occurrence of risk event number 1, the probabilities of the technology capability development and the product feature development will change. Figure 3.6 illustrates the effect of the new evidence (occurrence of Risk 1) on the model.

a)



b)

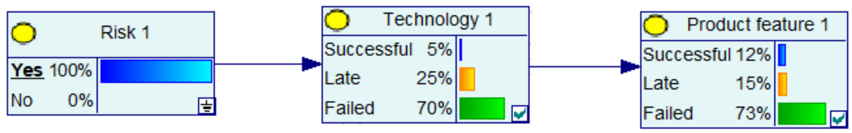


Figure 3.6 a) Bayesian network with no new evidence. b) Bayesian network given the occurrence of Risk 1.

As demonstrated in Figure 3.6, given the new evidence of Risk 1 occurrence, the success probability of Technology 1 has been reduced by 52%. On the other hand, its late development and failure probabilities have increased by 4% and 48%, respectively. Now, suppose the probability of Risk 1 is considered high, as suggested by Jeong et al. In that case, the roadmapping team might need to think of an alternative technological capability in case Risk 1 actually occurs. Hence, the entire plan is not either delayed or stuck. However, unlike the Jeong et al. model, this approach can be taken potentially in all of the roadmap layers in this framework. It means that if a technological capability was not considerably impacted in some circumstances, given the occurrence of a risk event, but a product feature probability was significantly decreased, the roadmapping team thought of an alternative product feature to meet the market demands.

Another scenario could be a risk event associated with one or multiple market drivers, an event that is not out of the ordinary for uncertain fluctuating markets. The roadmapping team could have thought of potential product features to address an anticipated alternative market demand for proper reaction to such circumstances. Figure 3.7 illustrates a situation in which another risk factor influences a market driver in addition to the influence of a risk factor on a technology capability.

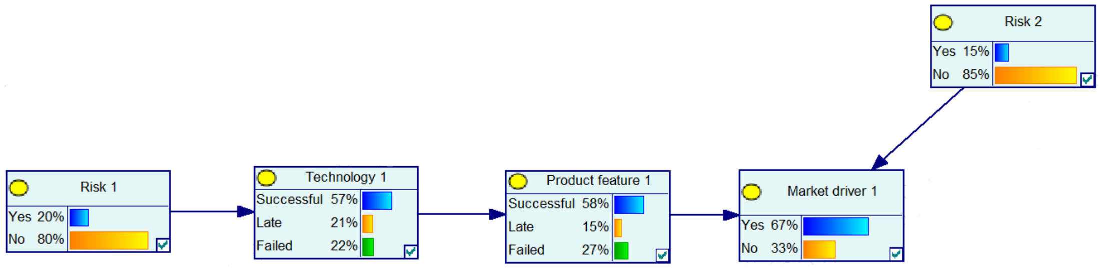


Figure 3.7. Bayesian Network with two risk nodes influencing a technological capability and a market driver

When product feature 1 influences market driver 1, market driver 1 cannot influence back product feature 1. In broader terms, the probabilistic dependencies only work one way in the Bayesian Network. Therefore, the mere change of probabilities of a child node under the influence of a risk event will not modify the probabilities of the parent nodes. The parent nodes' probabilities will be updated only if new evidence is available about a child node (only if we know for a fact that either of the states for a child node has occurred). As a result, a scenario in which Risk 2 and Market driver 1 are assumed as evidence can be simulated, and the consequences and impacts can be analyzed throughout the network.

Therefore, to investigate the change of probabilities in parent nodes in case of probability change in a child node caused by a risk event, an assumption needs to be made about the child node under the influence of the risk event. This will let the risk consequences reflect throughout the network. Therefore, it will be necessary to assume that one of the states of the child node has occurred according to its updated probabilities. For example, given the occurrence of Risk 2, the probabilities of market driver 1 (child node) will be updated. However, there will be no change in the parent nodes product feature 1, technology capability 1, and risk 1 (see Figure 3.8).

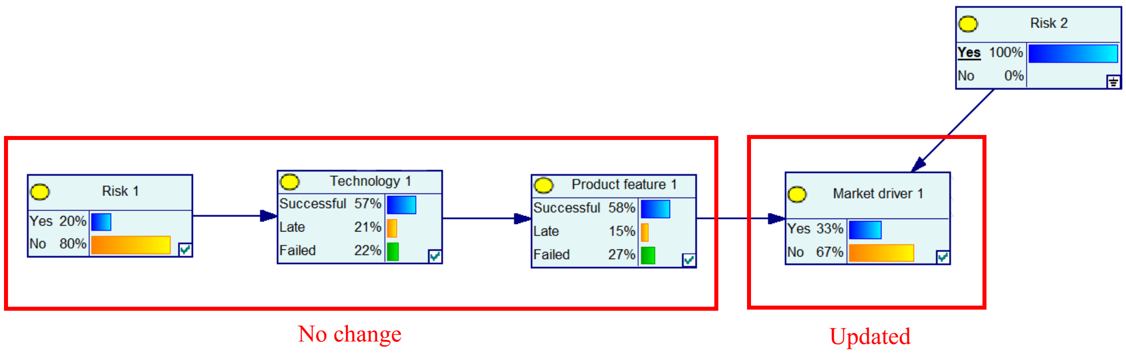


Figure 3.8 Bayesian Network - no change in parent nodes following probability change in the child node.

An assumption needs to be made about market driver 1, so the consequence of risk event 2 is reflected throughout the network. Referring to the updated probabilities of market driver 1 and investigating the risk 2 consequences in the network, it is only reasonable to assume that market drive will not be met (state set to NO). As the new evidence about market driver 1 not being met is assumed, the probabilities of the parent nodes will be updated (see Figure 3.9).

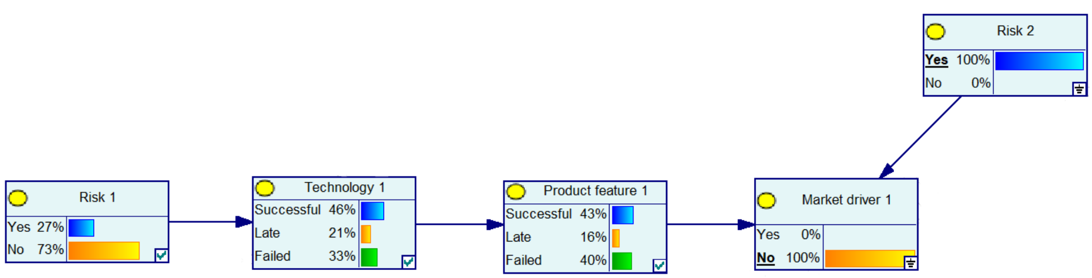


Figure 3.9 Bayesian Network - parent node probabilities updated.

Similar steps can be taken when a risk factor influences a product feature.

3.6. Enhancing the framework with ANP

Inspired by Szucs & Sallai's [102] effort on fault trees, this framework integrates the Analytic Network Model (ANP) into the Bayesian Network. Unlike the context of fault spreading, this framework investigates the spreading of positive contributions in meeting the roadmap's goal. The final goal of a roadmap -especially a market-pull roadmap- is to meet the market demands. Therefore, the focus will be on the market drivers. Thus, the market drivers will be weighted through ANP based on specific criteria defined by domain experts. Figures 3.10 and 3.11 show an ANP model with two clusters (market drivers and criteria). The connection between the clusters means that every node in 'Market drivers' is connected to every node in 'Criteria'. However, there is no inner relationship in a cluster.

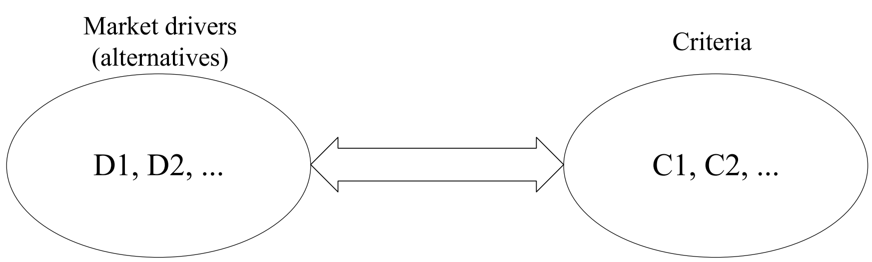


Figure 3.10 Nodes for two clusters for ANP procedure

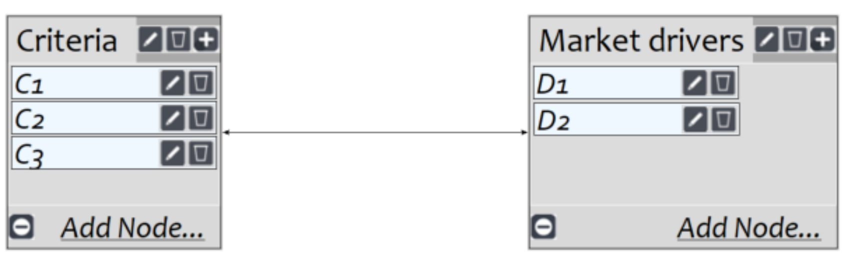


Figure 3.11 ANP model for two market drivers (D1, D2) and three criteria (C1, C2, C3)

After the experts identify the market drivers and prioritization criteria, a pairwise comparison will be conducted in both clusters with respect to the nodes of the other cluster. For example, in a model with two market drivers (D1, D2) and three criteria (C1, C2, C3), the paired-wise comparisons will be:

- Paired-wise comparisen of D1 and D2 wrt on C1

C1	D1	D2
D1	1	X
D2	1/X	1

- Paired-wise comparisen of D1 and D2 wrt on C2

C2	D1	D2
D1	1	Y
D2	1/Y	1

- Paired-wise comparisen of D1 and D2 wrt on C3

C3	D1	D2
D1	1	Z
D2	1/Z	1

- Paired-wise comparisen of C1, C2, and C3 wrt on D1

D1	C1	C2	C3
C1	1	A	B
C2	1/A	1	C
C3	1/B	1/C	1

- Paired-wise comparisen of C1, C2, and C3 wrt on D2

D2	C1	C2	C3
C1	1	D	E
C2	1/D	1	F
C3	1/E	1/F	1

After running the pair-wise comparisons, the unweighted supermatrix, weighted supermatrix, and limit supermatrix will be derived, and market drivers' importance (weight) will be calculated. (see tables 3.3-3.6).

Table 3.3 Unweighted Super Matrix

Clusters	Nodes	C1	C2	C3	D1	D2
Criteria	C1	0.000000	0.000000	0.000000	0.212208	0.237042
	C2	0.000000	0.000000	0.000000	0.725742	0.064343
	C3	0.000000	0.000000	0.000000	0.062050	0.698615
Market drivers	D1	0.166667	0.800000	0.500000	0.000000	0.000000
	D2	0.833333	0.200000	0.500000	0.000000	0.000000

In this example, because there are only two clusters and the matrix is already normalized, the weighted supermatrix is equivalent to the unweighted supermatrix (the numbers are based on arbitrary weights).

Table 3.4 Weighted Super Matrix

Clusters	Nodes	C1	C2	C3	D1	D2
Criteria	C1	0.000000	0.000000	0.000000	0.212208	0.237042
	C2	0.000000	0.000000	0.000000	0.725742	0.064343
	C3	0.000000	0.000000	0.000000	0.062050	0.698615
Market drivers	D1	0.166667	0.800000	0.500000	0.000000	0.000000
	D2	0.833333	0.200000	0.500000	0.000000	0.000000

Table 3.5 Limit Super Matrix

Clusters	Nodes	C1	C2	C3	D1	D2
Criteria	C1	0.111629	0.111629	0.111629	0.111629	0.111629
	C2	0.215712	0.215712	0.215712	0.215712	0.215712
	C3	0.172658	0.172658	0.172658	0.172658	0.172658
Market drivers	D1	0.277504	0.277504	0.277504	0.277504	0.277504
	D2	0.222496	0.222496	0.222496	0.222496	0.222496

Table 3.6 Priorities based on the Limit Super Matrix

Name	Normalized by Cluster	Limiting
C1	0.22326	0.111629
C2	0.43142	0.215712
C3	0.34532	0.172658
D1	0.55501	0.277504
D2	0.44499	0.222496

After normalizing by cluster, the priorities (weight) of the market drivers will be evaluated.

3.7. Vectorized Bayesian Network (VBN)

After evaluating the weight vectors of the market drivers (leaf nodes), the relative weight vectors of all the parent nodes will be determined. A relative weight vector can be calculated by multiplying the child node weight vector by conditional probability (see Equations. 7 and 8). Therefore, the Vectorized Bayesian Network (VBN) of an enhanced roadmap will contain five layers of market drivers, product features, technology capabilities, resources, and risks, and all layers contain nodes with probabilities and weight factors (see Figure 3.12). The relative weight of each node shows the average contribution of that node in meeting the market drivers. For example, W_{T1D1} is the first element of the relative weight vector of technological capability T1 and shows the contribution of T1 in meeting market driver D1. The relative weight analysis can also be conducted in the scenario with evidence in the Bayesian Network.

3.8. Risk-adaptive treatments

The goal of a roadmap is to meet the market demands. Throughout the roadmap, some elements contribute to meeting the market demands (resources, technological capabilities, product features, positive risks). However, some elements have a destructive effect (negative risks). The relative weight vectors measure the contribution of each element in meeting the market demands. As the relative weights are the result of the interaction of market drivers' importance (priorities) and the conditional probabilities throughout the network, the weight vectors of positive nodes will be calculated through the success probabilities of the nodes. In contrast, the weight vectors of negative nodes will be calculated based on the failure probabilities (whether "late" is considered a success or failure for this analysis is dependent on enterprise policies). This integration of ANP and VBN can give the decision-makers valuable insight into the contribution of each node of the roadmap in meeting the market demands or intercepting them and helping the experts make decisions about strategies for adapting to different circumstances.

The previous approaches identified the relationship between different nodes and layers in the roadmap; however, they failed to investigate their contribution. This is a critical aspect that Jeong et al. did not take into consideration in their risk-adaptive approach.

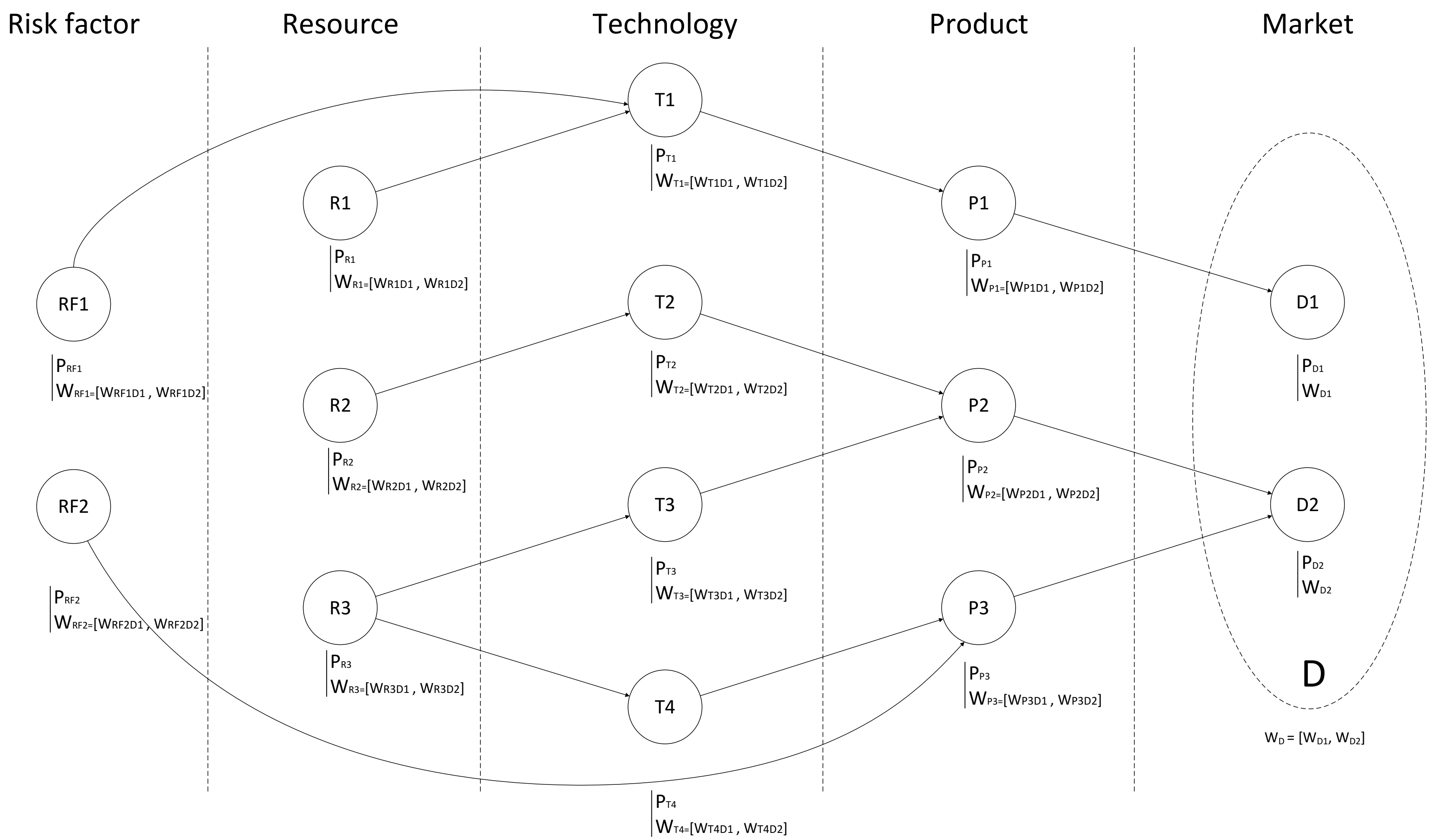


Figure 3.12 Vectorized Bayesian Network of the example roadmap

The ANP/VBN analysis can be used in different situations. It can be conducted on a network with zero evidence or under different circumstances where one or multiple pieces of evidence are available.

This investigation can give valuable insight into whether a node sufficiently contributes to the goal or its contribution is not considerable. For example, suppose a positive node’s contribution is negligible, yet it requires vast resources (financial or human resources). In that case, the team can think of an alternative element that can have an equal or better positive contribution given the relationships and the risks while requiring fewer resources. The weight vectors can also provide valuable information about how damaging a risk can be to a market driver. By developing the weight vectors based on the failure probabilities of the nodes, we can figure out the contribution of each risk factor in the interception of achieving the roadmap goals. The team can always consider modifications, so the plan is less exposed to the risk factors, and meeting the market drivers is less intercepted.

Moreover, in scenario-based analysis, if a piece of evidence becomes available, the probabilities and weight vectors will be updated accordingly. The change in the probabilities (as discussed in the Bayesian Network section) and the weight vectors elements will demonstrate the impact of the evidence on the model. If the new evidence happens to be a risk event in a scenario, the change of probabilities and weight vectors will show how vulnerable a node can be to that risk. Also, the updated probabilities and weight vectors will show if a node will sufficiently contribute to the goal under different circumstances in different scenarios. If the contribution of a node drops to a negligible amount in a scenario, that node can be replaced in case that scenario occurs.

To summarize, the Vectorized Bayesian Network on technology roadmap developed based on Bayesian Network, and ANP can analyze all the three aspects of risk; probabilities, consequences, and impacts in different scenarios.

The procedure of ANP and VBN integration as well as the general process of the enhanced T-plan can be seen in Appendix D, Figure D.1 and D.2, respectively.

Chapter 4

Methodology

4.1. Introduction

This research was an applied study aimed to provide enterprises, senior managers, and technology and product development experts with an agile and flexible roadmapping framework for developing new technologies. A framework that involves creative problem-solving and quantitative analysis for considering real-world uncertainties. In the meantime, it provides a balance between technology push and market pool. As discussed in the literature review section, there have been many efforts to improve and enhance the TRM method, while quantitative analysis and uncertainty have always been among the most struggling aspects of the topic. Therefore, the effort of this research was focused on integrating these two perspectives in the roadmapping process and developing an enhanced roadmapping approach, especially for the development of new state-of-the-art technologies.

4.2. Research Design

For developing an enhanced TRM framework, it was necessary to conduct a thorough review of the literature of TRM, its limitations, and potential opportunities for improvement. Also, a case study was conducted on developing ice-phobic coatings with Bell Textron Canada Limited to explain and elaborate the framework. As a strategic planning tool, the nature of the technology roadmap necessitates the involvement of both quantitative and qualitative data. Therefore, an exploratory sequential design was adopted. In this design, the qualitative data was collected and analyzed to explore the context, develop an initial understanding of the problem, and construct a general model, followed by the quantitative data to supplement and specify it. Also, as the context of new technologies and the limited literature of specific subjects suggest, the data collected for this study was both primary and secondary, describing the problem and context without intervention.

4.2.1. Methodology rationale

The rationale underpinning this methodology lies in the nature of technology roadmaps. Technology roadmaps are mid-range/long-range thorough strategic maps meant to provide a visual presentation of the steps needed to be taken to meet specific goals. For the roadmaps to be developed, however, enormous efforts must be made in terms of the preparation, and a complex process must be accomplished. This process involves different qualitative aspects such as the roadmap drivers and their dependencies and quantitative aspects such as the probabilistic and decision-making models. Therefore, the best way to approach technology roadmaps is to adopt a mixed data type strategy.

Moreover, as this study aims to develop a framework for developing state-of-the-art technologies, the available literature on the subjects is limited. On the other hand, considering the high level of innovation, the complexity of the problems, and the inaccessibility of experts, expert knowledge alone might not be sufficient. Therefore, this study has adopted a mixed approach with both primary and secondary data.

4.2.2. Methods of data collection

After having an exhaustive literature review on TRM and gathering information about its process, potential integrations, and applications, an enhanced framework was proposed to address the planning of new state-of-the-art technologies development. A pilot study was conducted on ice-phobic coatings, a project run by Bell Textron Canada Limited. Ice-phobic coatings are one of the greatest current struggles of the aerospace industry that require advanced technologies to address. For this case study, as discussed above, it was necessary to collect both qualitative and quantitative data. Interviews were held with Bell Textron experts. The experts were purposively selected according to the relevance of their area of expertise to the subject under investigation. The participants were either directly or indirectly involved in the previous efforts about ice-phobic coating or were academic scholars that had worked on this subject or relevant topics. Due to the extent of the subject and the multiple aspects involved, the selected experts for the interviews came from different disciplines. Therefore, semi-structured time-flexible interviews were held so that while covering the critical aspects, the experts would have the opportunity to bring up new angles. The semi-structured interviews were necessary because the research was following an exploratory path, maneuvering on a problem requiring state-of-the-art technology. However, the fundamental structure of the interview was developed based on the limited literature available on the subject. As the competitive market of aerospace technology and the challenging problem suggest, minimal literature was available on the subject for two reasons. Foremost, the advancement of the technologies addressing the problem has been minimal. Second, that minimal advancement has not been published due to market competition and sensitivity of the information. Therefore, basically, as much as possible, every available publication on the subjects was gone over, and valuable information and insights were extracted from them.

As the result of the qualitative data, major variables (roadmap drivers and elements) and connections between the variables (dependencies) were identified, and general models (ANP and Bayesian Network) were developed. Therefore, the study could move forward to quantitative data collection and feeding the models. For quantitative data collection, Likert scale questionnaires were designed to address the pair-wise comparisons for ANP models. Another questionnaire was designed to address the conditional probability distribution of the Bayesian Network nodes. The weight vectors of the Vectorized Bayesian Network were derived based on the ANP output of market drivers, and the involvement of the experts in evaluating them was not necessary. In addition to the surveys, Bell Textron provided some information on the previous attempts to develop ice-phobic technology, the limited available literature on ice-phobic materials, and their application in the aerospace industry. Although this information was insightful, it did not help with the quantitative data collection.

4.2.3. Methods of Analysis

After collecting the qualitative data through interviews, a thematic analysis was conducted on the data. It involved listing the drivers and product features mentioned by the experts and selecting, grouping, and clustering the most repeating ones. As a result, the market drivers and product features were identified, and a good understanding of the context and problem was gained. Next, potential technological capabilities were identified through multiple TRIZ tools, and their connections with the upper layer were established. Given the potential technological capabilities, technology gaps were identified, and the corresponding resources were determined. Finally, the non-intrinsic risks associated with roadmap elements were recognized, and the basic structure of the roadmap was completed.

In the next step, following quantitative data collection (paired-wise comparisons), the market drivers were prioritized by an ANP model through specific criteria identified by the experts in the interviews. Afterward, the elements of every other layer of the roadmap were also prioritized by multiple ANP models with respect to the elements of the upper layer as the criteria. The software used for constructing and analyzing the ANP models was SuperDecisions 3.2.0. Finally, the primary roadmap developed based on the qualitative data was supplemented by ANP priorities in the next stage. Besides the possibility of selecting a limited number of elements to address, the priorities could help verify the consistency of the associations and dependencies mentioned by the experts.

In the next step of quantitative data analysis, the probabilistic aspects of the model were to be involved. Therefore, the elements were turned into nodes, and the relationships were translated to arcs of a Bayesian Network based on the time frames, conditional probabilities, and dependencies derived from the expert knowledge through questionnaires. Finally, the weight vectors of the nodes were evaluated based on the ANP result of the market drivers, and the Vectorized Bayesian Network (VBN) of the roadmap was developed. After developing the probabilistic model, the roadmap's final draft was charted, different scenarios were analyzed, and adaptive strategies were suggested. The Bayesian Network models were constructed and analyzed by GeNIe Academic Version 3.0.6518.0.

Figure 4.1 illustrates the adopted mixed-method research design.

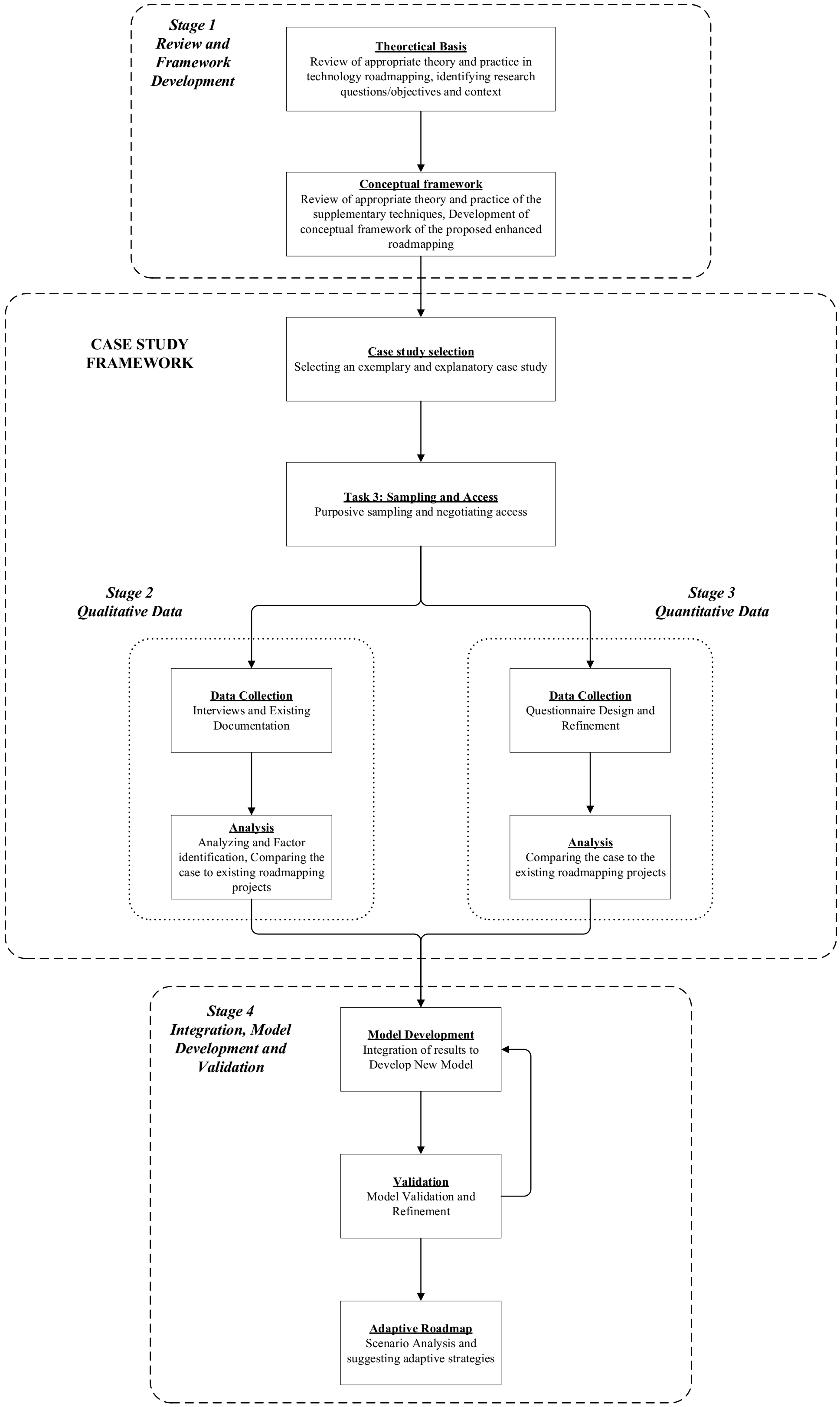


Figure 4.1 The adopted mixed method Research Design

4.3. Tools and Materials

4.3.1. SuperDecisions

SuperDecisions [103] is a free educational decision-making software based on the Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP) [104]. This software is a simple, easy-to-use package for constructing decision models with dependence and feedback and computing results using supermatrices of the Analytic Network Process, a mathematical theory for decision-making developed by Thomas L. Saaty [105].

The conceptual models corresponding to the prioritization in each workshop of the enhanced T-plan were modeled and analyzed by SuperDecision (version 3.2.0) according to the official SuperDecision guide published by William and Saaty [106]. Therefore, for each prioritization stage, the corresponding nodes were created according to the conceptual model, the connections were added, and finally, the model was fed by the result of paired-wise comparison questionnaires. As a result, the priorities were calculated by the software.

4.3.2. GeNIe Academic

GeNIe Academic [107] is a free tool for interactive model building and learning. GeNIe allows for building models of any size and complexity, limited only by the capacity of the operation memory of the computer. This modeling software is compatible with the Structural Modeling, Inference, and Learning Engine (SMILE), a fully platform-independent library of functions implementing graphical probabilistic and decision-theoretic models, such as Bayesian networks [108].

The probabilistic models corresponding to the risk analysis section of this study were modeled and analyzed by GeNie Academic (version 3.0.6518.0) according to the GeNie Modeler User Manual [108]. Therefore, for the risk models and scenario analysis, the elements of the roadmap were created as probabilistic nodes. Afterward, the connections were added, and the model was fed by the probability distributions derived from questionnaires. As a result, the conditional probabilities of the nodes were calculated by the software. Also, by setting the probabilities of different nodes on 100% of any of the probability states, different evidence-based scenarios were simulated and analyzed.

4.4. Limitations and Assumptions

As mentioned before, the quality of a roadmap depends on the number of participants in developing the roadmap, the diversity of the participants' backgrounds, competence of the experts involved in defining the forecast, and how legitimate a company adopts a vision and uses solutions from the technology roadmap [67]. As the proposed framework requires the contribution of many industry experts from different disciplines related to the problem, the adopted procedure's greatest limitation is the lack of a sufficient number of experts. Considering the sensitivity of the industry and information confidentiality, accessing the experts and related documents was one of the most complex parts of the process. Bell Textron had not thoroughly covered the problem under investigation, and different parts of the project have been outsourced to other companies in the previous attempts. These companies were in charge of different technical aspects of the project, and because the contracts were terminated, those companies' expert was not reachable. Therefore, all facts together, even after accessing the available Bell Textron experts and documents, limited accurate information could be obtained. Also, due to the unexplored and competitive context of the problem, minimal literature was available on the subject. Therefore, building reliable technical information from these two sources was a significant challenge throughout this research.

In this situation, lab tests could have been an answer to the lack of accurate information. However, the lab tests and the access to experts were suffocated by the 2020-2021 global pandemic due to the COVID19 crisis. During this research, Bell Textron, like many other companies, worked almost entirely remotely with strict health protocols. Therefore, despite the framework recommending in-person workshops with all parties present in the same room, all the meetings and interviews were held online in different time slots. Had things been in regular order, the research could have involved more experts, more efficient meetings, and potentially some lab tests. Therefore, the numbers would have been more accurate in the models. However, the procedure followed is still a solid explanatory case study to demonstrate the proposed framework.

Due to the unusual circumstances, the most significant assumption in the research was in response to the potential information inaccuracy. For example, both the qualitative data (elements and connections) and the quantitative data (priorities and probabilities) could potentially be more accurate if more experts discussed them in in-person meetings. Therefore, the information obtained from the limited resources available was assumed accurate enough for the sake of case study progression and framework demonstration.

Another assumption was made about the three probability states for technology, product, and market nodes in the Bayesian Network. These states could be different depending on company policies and the market environment. For example, in some companies and market environments, a late delivery could still be beneficial. However, late delivery might mean an absolute failure in another environment if a competitor delivers first and conquers the market.

In addition, due to the lack of expert knowledge on specific fields of science involved in the study, the resource allocations to the selected technological capabilities were assumed equal. Therefore, no comparison was made between the resources in the ANP model.

Finally, an assumption was made about the certainty of the market for ice-phobic technology. According to the market and literature, a practical and reliable ice-phobic coating solution could be revolutionary in the aerospace industry. It is because in cold climates with considerable icing effects, vertical flying vehicles encounter severe challenges, and the entire vertical flight fleet might be shut down during the winter in some countries. Therefore, in this study, no risk factor was considered for the market. However, in other business environments, the market might have uncertainties that need to be considered.

Chapter 5

Case study and Results

5.1. Ice-phobic Coating Solution

The aviation industry has had various advancements during recent decades that have made air travel safer than ever. However, the accumulation of ice on airplane and rotorcraft wings remains one of the most challenging problems in the aviation industry [109]. Especially for rotorcrafts, the entire fleet simply cannot operate during the winter in some extreme climates, which can be a great loss for aviation companies. Therefore, the industry desires a reliable and efficient deicing or anti-icing system so the fleet can still operate in extreme weather. Figure 5.1 summarizes the techniques to address this problem.

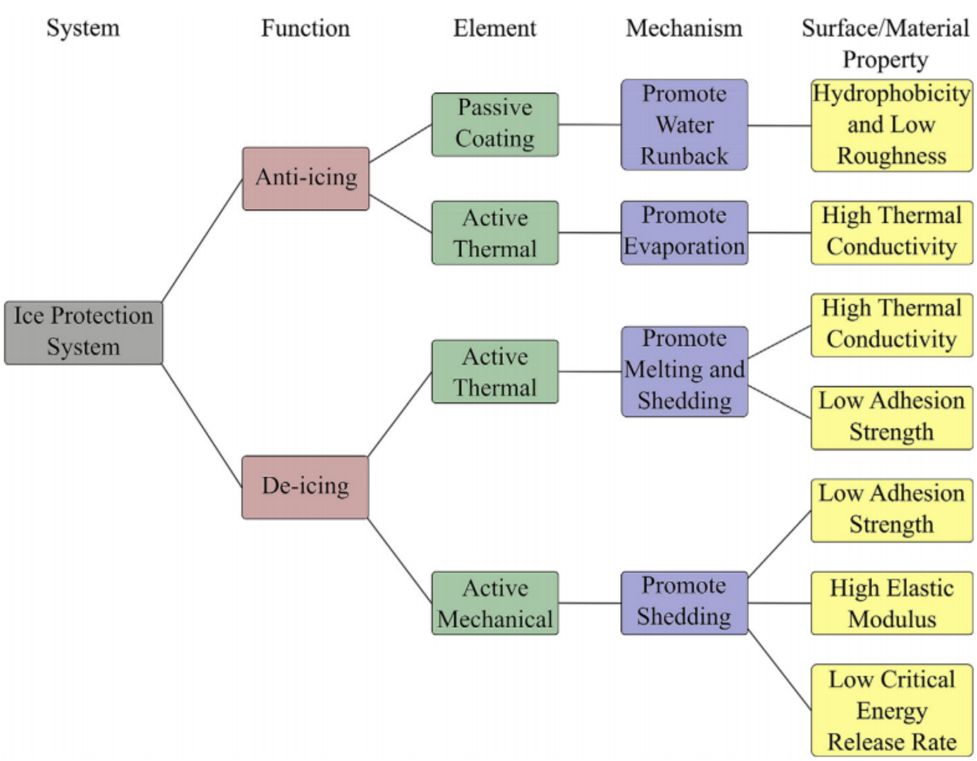


Figure 5.1 Summary of de-icing and anti-icing techniques [110]. Adapted from Tepylo et al. (2019).

Currently, the rotorcrafts are deiced through electro-thermal systems. In these systems, the ice accumulated on the rotor-blades is melted down by heating coils running along the span or chord of the blades. However, the electro-thermal systems are not very efficient as they are slow and have enormous energy consumptions [109]. Hence, it will be hazardous to fly the rotorcraft under severe icing conditions. Therefore, there have been efforts to develop new solutions for the problem. One of the recent areas of focus has been anti-icing and ice-phobic coatings.

Ice-phobic materials are materials that hinder ice from forming on surfaces by reducing the ice adhesion. They can be used in the form of coatings on different surfaces. Due to their benefits, ice-phobic coatings have various fields of application, such as aviation, wind energy, and the automotive industry. However, they are not widely used due to unsolved technical challenges in many sectors [111].

This case study focuses on developing a technology roadmap to address the market drivers for ice-phobic coatings.

5.2. Roadmap development

5.2.1. Market drivers

Tables 5.1 shows the identified market drivers for ice-phobic coatings and their definition.

Table 5.1 Market drivers and definition for the ice-phobic coating solution

	Market Drivers	Definition
D1	Low cost	Refer to a low cost of mass production and acquisition
D2	Easy to apply	Refers to no special tools required for application
D3	Fast application/drying	Refers to a minimal time to apply and dry
D4	Durability	Refers to no loss of properties between major maintenance activities
D5	Maintainability	Refers to no extra maintenance required
D6	Uniformity	The identical finishing on every blade guaranteeing interchangeability
D7	No harmful effect	No interfere with critical functionality of the aircraft
D8	Effectiveness	Refers to a successful ice-phobic effect

The identified market drivers were prioritized through an ANP model with performance and functionality as the criteria. To be the first to enter the market with an ice-phobic coating solution, the functionality was prioritized over the performance, which could be continuously improved in the subsequent releases. Figure 5.2 illustrates the ANP model for market drivers' prioritization.

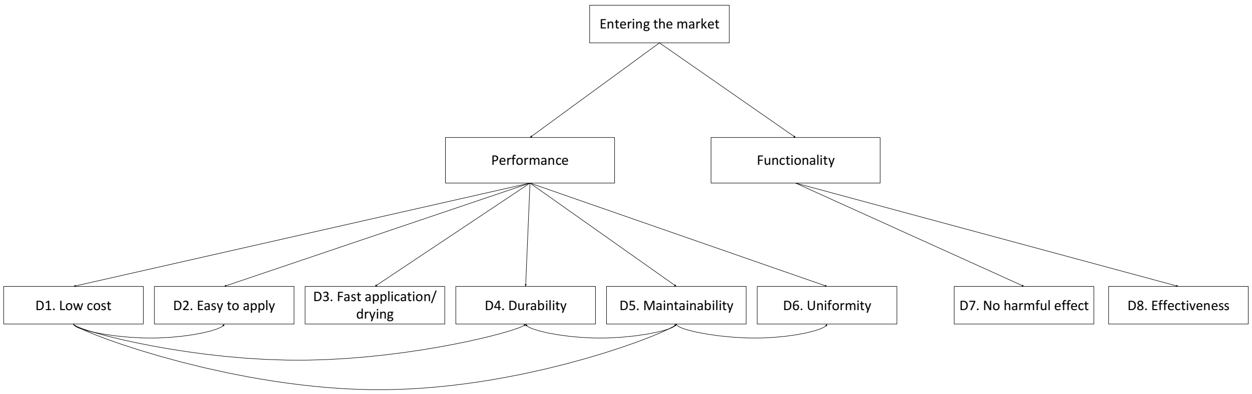


Figure 5.2 ANP model for prioritization of the market drivers

The developed ANP model was built in SuperDecision software, and results were derived.

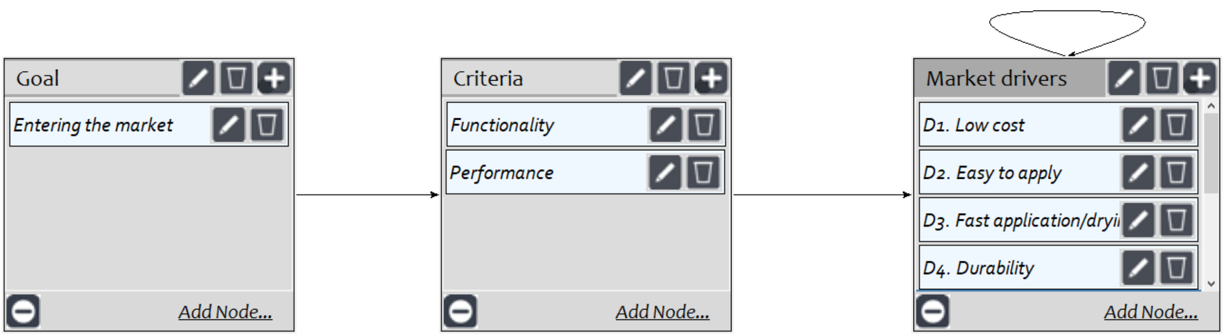


Figure 5.3 ANP model for prioritization of the market drivers in SuperDecision software

Tables 5.2 and 5.3 show the derived priorities for the market drivers. Also, the corresponding paired-wise comparisons are available in Appendix F.

Table 5.2 Market drivers' priorities

Clusters	Nodes	Entering the market
Criteria	Functionality	0.436851
	Performance	0.054606
Goal	Entering the market	0.000000
Market drivers	D1. Low cost	0.002322
	D2. Easy to apply	0.007181
	D3. Fast application/drying	0.006781
	D4. Durability	0.022955
	D5. Maintainability	0.014763
	D6. Uniformity	0.017690
	D7. No harmful effect	0.145617
	D8. Effectiveness	0.291234

Table 5.3 Market drivers priorities normalized by cluster

Name	Normalized by Cluster	Limiting
Functionality	0.88889	0.436851
Performance	0.11111	0.054606
D1. Low cost	0.00457	0.002322
D2. Easy to apply	0.01412	0.007181
D3. Fast application/ drying	0.01333	0.006781
D4. Durability	0.04514	0.022955
D5. Maintainability	0.02903	0.014763
D6. Uniformity	0.03479	0.017690
D7. No harmful effect	0.28634	0.145617
D8. Effectiveness	0.57268	0.291234
Entering the market	0.00000	0.000000

5.2.2. Product features

In the next step, corresponding product features were identified to address the market drivers. Table 5.4 shows the product features and their definitions.

Table 5.4 Product features and definitions for the ice-phobic coating solution

	Product Features	Definition
P1	Compatibility with other chemical layers	product will not have an adverse effect on the other coatings used for finishes
P2	ARF	ARF shall be no less than 6
P3	Erosion resistance	Erosion resistance shall be no less than 65,000 (number of impacts)
P4	Corrosion resistance	ISO 12944 compliance
P5	Fast dry	Not more than 24 hours to completely dry
P6	Surface uniformity	The thickness needs to be consistent
P7	Low weight	The product shall not weigh more than current finish coatings
P8	Self-healing	Ability to repair physical damage or recover functional performance with minimal intervention
P9	Self-cleaning	the coating will clean itself with minimal or zero-intervention
P10	Strong adhesion to the blade (mechanical strength)	for longer-lasting protection
P11	Transparency	so can be applied to any painted or non-painted surface
P12	Size and shape	The size and shape of the coating layer should not interfere with aerodynamics

After identifying the product features, an analysis grid was constructed to investigate the connections between the market drivers and product features (see Table 5.5).

Table 5.5 Analysis grid for Market Drivers and Product Features

Product Features	Market Drivers							
	D1	D2	D3	D4	D5	D6	D7	D8
P1		+	+					
P2								+
P3				+				
P4				+				
P5			+					
P6						+	+	
P7	+	+	+					
P8				+	+			
P9				+	+			
P10				+	+			
P11							+	
P12	+	+	+			+	+	

The analysis, however, could not show the importance of each product feature overall or with respect to a particular market driver. Therefore, an ANP model was developed to prioritize the product features. The criteria for this ANP model were the market drivers (see Figures 5.4 and 5.5).

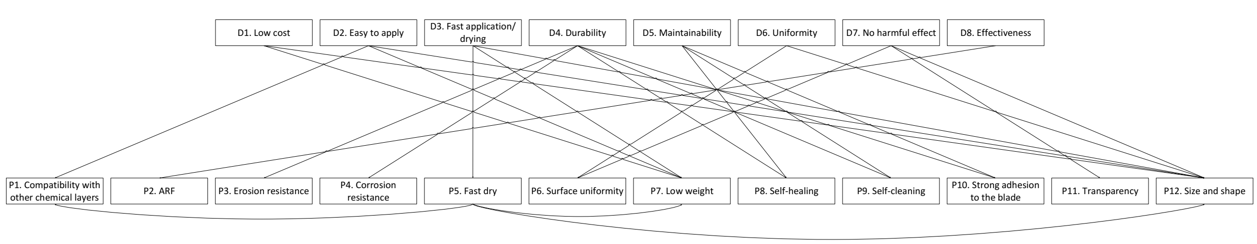


Figure 5.4 ANP model for prioritization of the product features

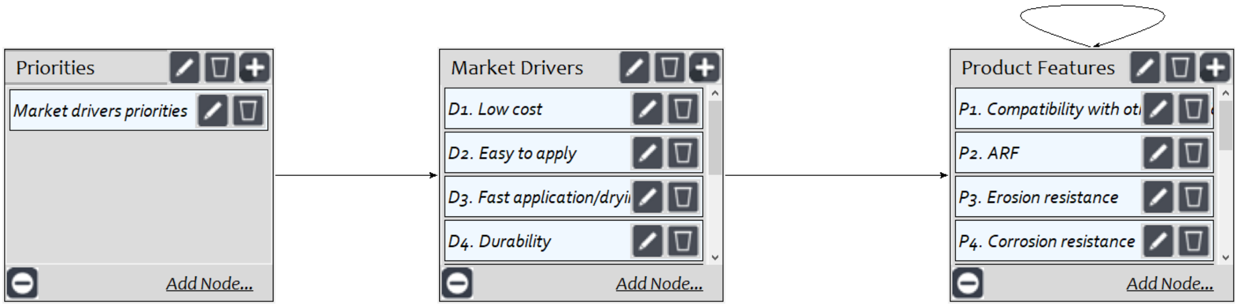


Figure 5.5 ANP model for prioritization of the product features in SuperDecision software

As the weights (priorities) of the market drivers were derived in the previous step, they were directly put into use as the weights for the criteria of the new ANP model (see Table 5.6).

Table 5.6 Weights for the criteria of market drivers-product features ANP model

Graphical | Verbal | Matrix | Questionnaire | Direct

D1. Low cost	0.00457
D2. Easy to apply	0.01412
D3. Fast application~	0.01333
D4. Durability	0.04514
D5. Maintainability	0.02903
D6. Uniformity	0.03479
D7. No harmful effec~	0.28634
D8. Effectiveness	0.57268

Tables 5.7 and 5.8 show the priorities of the product features. Also, the corresponding paired-wise comparisons are available in Appendix F.

Table 5.7 Product features priorities.

Product Features	P1. Compatibility with other chemical layers	0.002777
	P2. ARF	0.285300
	P3. Erosion resistance	0.008698
	P4. Corrosion resistance	0.008188
	P5. Fast dry	0.003632
	P6. Surface uniformity	0.075236
	P7. Low weight	0.003184
	P8. Self-healing	0.009784
	P9. Self-cleaning	0.005227
	P10. Strong adhesion to the blade (mechanical strength)	0.005052
	P11. Transparency	0.009510
	P12. Size and shape	0.085227

Table 5.8 Product features priorities normalized by cluster.

Name	Normalized by Cluster	Limiting
P1. Compatibility with other chemical layers	0.00553	0.002777
P2. ARF	0.56854	0.285300
P3. Erosion resistance	0.01733	0.008698
P4. Corrosion resistance	0.01632	0.008188
P5. Fast dry	0.00724	0.003632
P6. Surface uniformity	0.14993	0.075236
P7. Low weight	0.00634	0.003184
P8. Self-healing	0.01950	0.009784
P9. Self-cleaning	0.01042	0.005227
P10. Strong adhesion to the blade (mechanical st~	0.01007	0.005052
P11. Transparency	0.01895	0.009510
P12. Size and shape	0.16984	0.085227

The priorities of product features with respect to a particular market driver were also derived through the same limit supermatrix. For example, Table 5.9 shows the priorities of product features P3, P4, P9, and P10 with respect to market driver D4.

Table 5.9 The priorities of product features P3, P4, P9, and P10 with respect to market driver D4.

Clusters	Nodes	D4. Durability
Product Features	P1. Compatibility with other chemical layers	0.000000
	P2. ARF	0.000000
	P3. Erosion resistance	0.386795
	P4. Corrosion resistance	0.364101
	P5. Fast dry	0.000000
	P6. Surface uniformity	0.000000
	P7. Low weight	0.000000
	P8. Self-healing	0.088055
	P9. Self-cleaning	0.041478
	P10. Strong adhesion to the blade (mechanical strength)	0.119571
	P11. Transparency	0.000000
	P12. Size and shape	0.000000

5.2.3. Current state analysis

Once the market drivers and corresponding product features were identified, it was time to start working on potential solutions. Therefore, different TRIZ tools were used to analyze the system's current state, identify critical elements and map their relationships. Finally, as a result, thirteen technological capability alternatives were suggested that could address different product features.

Foremost, a function analysis was conducted to identify the system, elements, and environment. Figure 5.6 illustrates the result of function analysis showing the elements in contact with the system and the ones having a harmful effect on the system's functionality and/or performance.

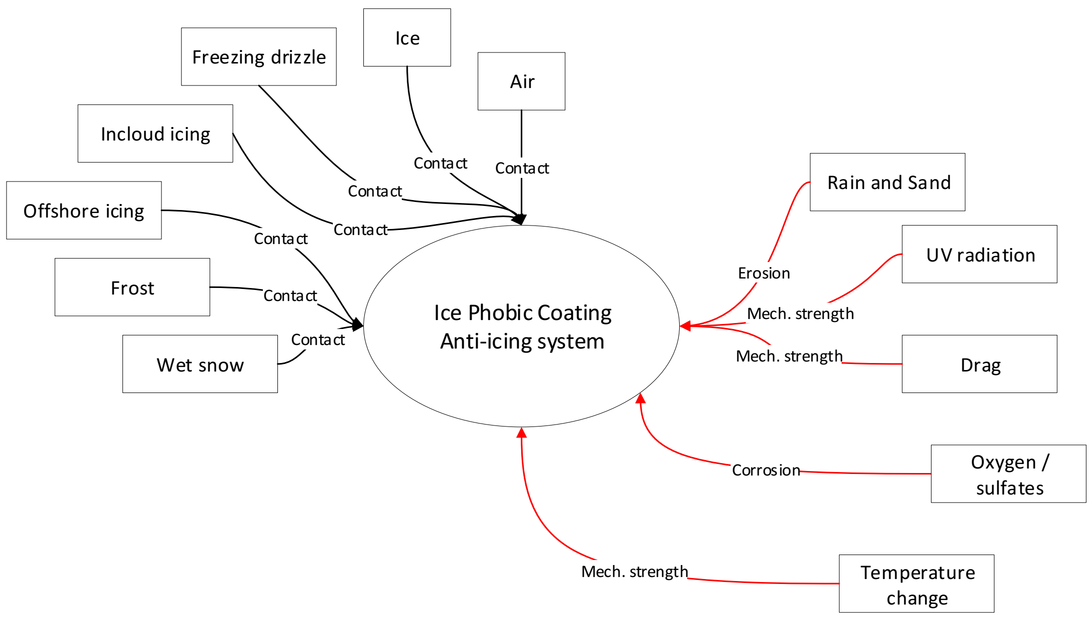


Figure 5.6 Function analysis of ice-phobic coating solution

A Su-field analysis was also conducted to investigate the interaction between the two main elements of the system. Figure 5.7 illustrates coat and ice being in a relationship through the mechanical field of icephobicity. It also shows that among the four system types introduced in Fig 2.27 of chapter two, the current system is identified as an ineffective complete system that requires improvement to create the desired effect.

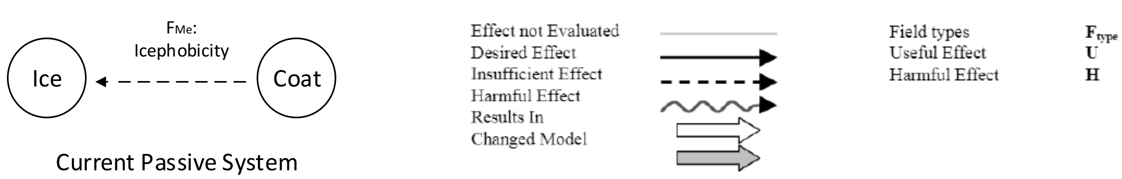


Figure 5.7 Su-Field analysis of ice-phobic coating system

Therefore, the insufficiency of the icephobicity field was the priority to address to assure functionality. Afterward, the other harmful effects identified in the function analysis could be addressed respectively.

5.2.4. Future state analysis

Once the system's current state became clear, it was time to picture a future for the coating solution. Therefore, a nine-window and ideal final result analysis were conducted. Figure 5.8. illustrates the nine windows summarizing the system and its sub- and super-system in the past, present, and future perspectives.

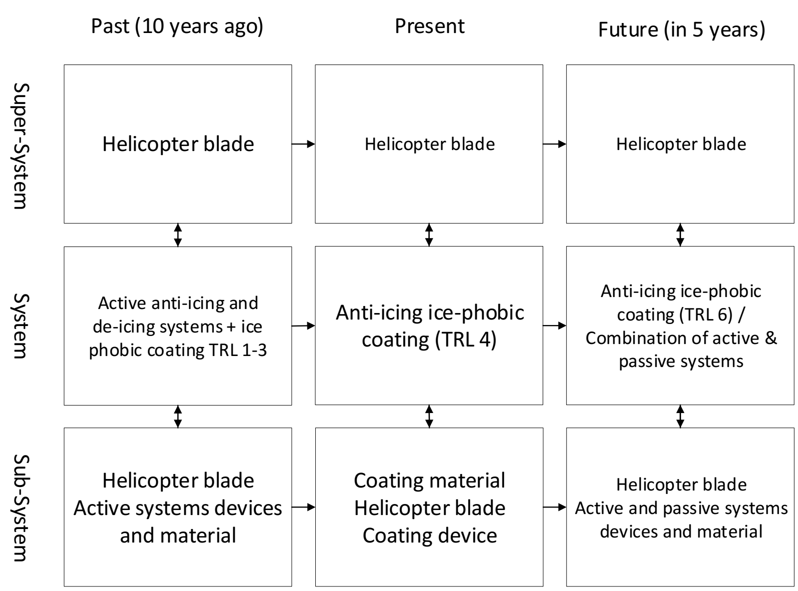


Figure 5.8 Nine-windows analysis for the ice-phobic coating solution

As Figure 5.8 suggests, the system could not exceed TRL 3 in the past, and it is currently in TRL4. The goal is to meet TRL 6 so that the coating solution can enter the market. Also, the perspective is to combine both active and passive systems to maximize performance.

In addition, an ideal final result analysis was conducted to investigate the factors to optimize (see Figure 5.9). As illustrated, in an ideal theoretical result, either there would be no need for an ice-phobic coating, or the supersystem would ensure the function. Therefore, there would be no energy consumption or maintenance. Hence, the ideal realistic result would be a system ensuring the function with controlled and optimized factors.

Of course, this system must move towards ideality by maximizing the benefits and minimizing the costs and harmful effects over time. However, as the evolution curve shows, ice-phobic coatings are at their birth phase. Therefore, they are at their lowest ideality and highest difficulty level.

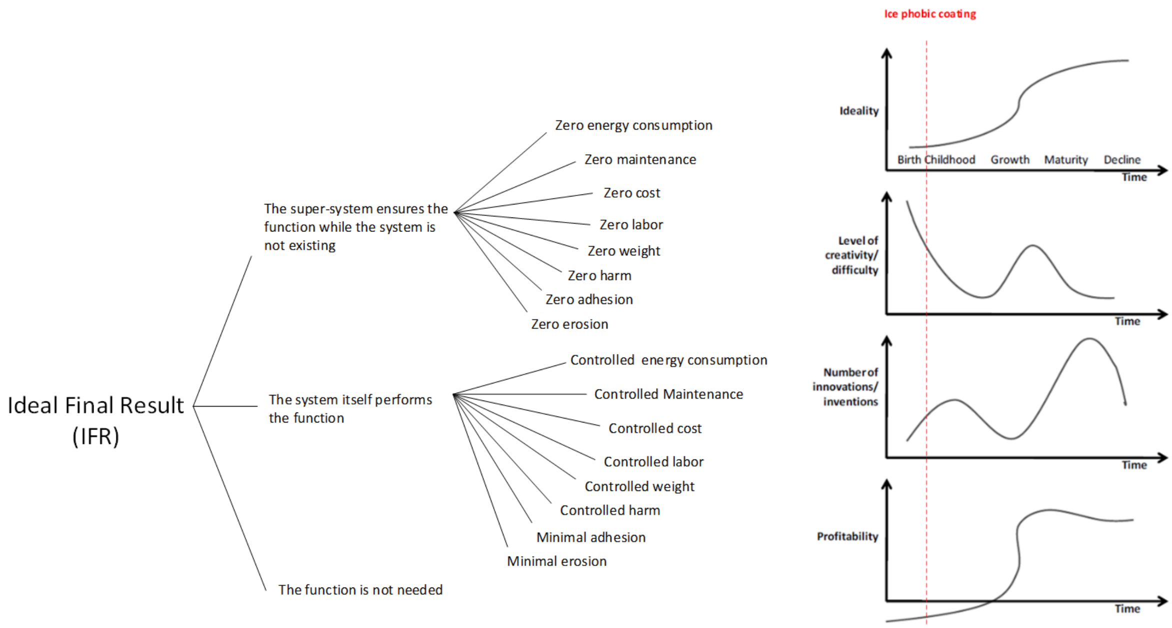


Figure 5.9 Ideal Final Result analysis and S-Curve for ice-phobic coatings

5.2.5. Technological Capabilities

After analyzing the system's current state and picturing a prospective future, thirteen technological capabilities were identified and suggested after an exhaustive literature review and expert discussion. Table 5.10 shows the technological capability alternatives, along with information about their developing companies, trademarks, and current status.

Table 5.10 Technological capabilities for the ice-phobic coating solution.

	Technological Capabilities	Solution category/Company	Status	Definition
T1	Nano/microstructured porous material	SLIPS	Developing	Coating solution based on nano/microstructured porous material infused with a lubricating fluid.
T2	Lubricant-infused surfaces	SLIPS	Developing	A liquid lubricant is stabilized by capillary forces within a porous or nanostructured solid
T3	High-conductivity carbon nanotube	HeatCoat™	Developing	High heat/thermal conductive coating layer
T4	Powerd heating	HeatCoat™	Existing	Heating the surface
T5	Chemical reaction	CG2 NanoCoatings	Existing	Micro-scaled chemical reaction on the surface
T6	Icephobic carbon nanotube	Equinor ASA	Developing	Adhesion reduction with single-walled carbon nanotube array (CNTA)
T7	Freezing point depression	Tailored coating systems	Developing	A drop in the temperature at which a substance freezes
T8	Anti-freeze proteins' peptides	Tailored coating systems	Developing	A class of small-molecule proteins or protein hydrolysates
T9	Plasma technology	Nano and micro-structured coatings using plasma technology	Developing	Materials on plasma state
T10	Nanoparticles	“Nano-textured,” super-hydrophobic coatings	Developing	Using nanoparticles for superhydrophobic surfaces
T11	Gentoo	Gentoo hydrophobic ice-phobic coating technology	Developing	A combination of silane-modified urethane cross-linked with tetraethoxysilane and possible metal catalyst in an alcohol solvent
T12	Nanoimprint lithography	active deicing/anti-icing technology for increased effectiveness	Developing	Using nanoimprint lithography to etch a superhydrophobic surface topography into the surface of a hard coating material
T13	Self-bonding polymers	HygraTek LLC	Developing	Ice delamination propagation coating

After identifying the technological capabilities, an analysis grid was constructed to investigate the product features each technological capability could address (see Table 5.11). Of course, the absence of a connection in the analysis grid does not mean that a technology capability does not address a particular product feature whatsoever. The connections, however, highlight the product features that are outstandingly addressed by each technological capability.

Table 5.11 Analysis grid for Product Features and Technological Capabilities.

	Product Features											
Technological Capabilities	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
T1	+	+				+	+		+			+
T2		+							+			
T3	+	+	+		+	+	+					+
T4		+										
T5	+	+			+	+	+	+				+
T6		+				+	+		+			+
T7		+										
T8		+						+				
T9		+					+				+	
T10	+	+										
T11		+	+	+						+		
T12		+		+								
T13		+			+	+				+		+

Although the analysis grid demonstrated the connection between the technological capabilities and the product features, it would not provide us with any information about the potential contribution of each technological capability in achieving a particular product feature. Therefore, an ANP model was constructed to rank the technological capabilities based on their cumulative contribution in meeting the product features. Figure 5.10 illustrates the ANP model for ranking the technological capabilities.

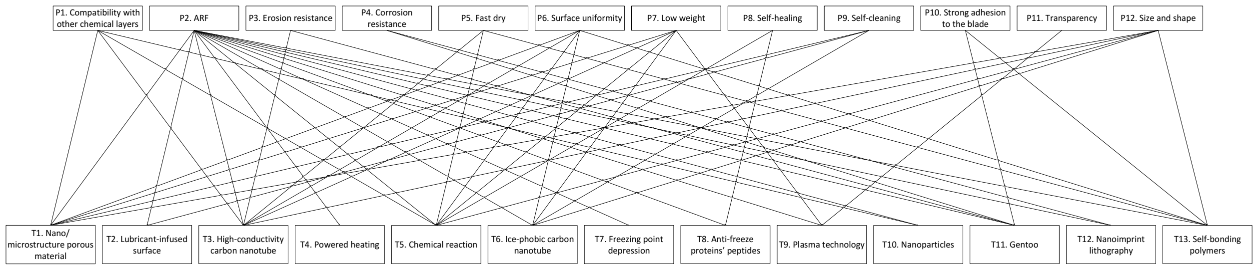


Figure 5.10 ANP model for prioritization of the technological capabilities.

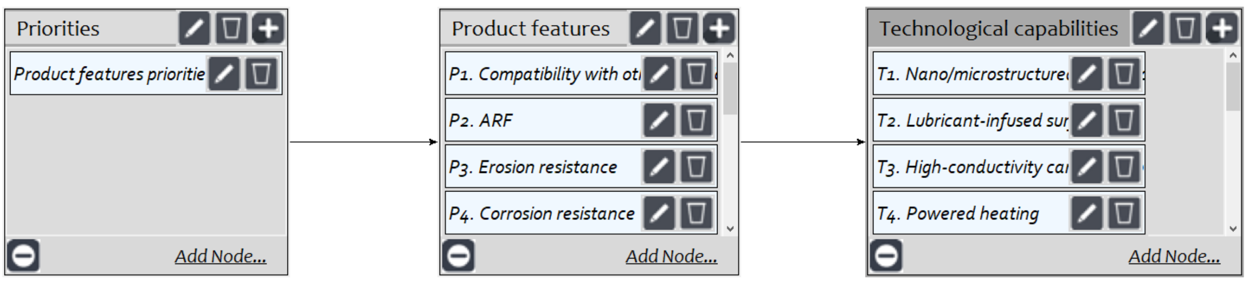


Figure 5.11 ANP model for prioritization of the technological capabilities in SuperDecision software.

As the model criteria were the product features, the priorities derived for product features in the previous step were directly used as the weight of criteria (see Table 5.12).

Table 5.12 Weights for the criteria of Product Feature - Technological Capability ANP model

Graphical | Verbal | Matrix | Questionnaire | Direct

P1. Compatibility wi~	0.00278
P2. ARF	0.2853
P3. Erosion resistan~	0.0087
P4. Corrosion resist~	0.00819
P5. Fast dry	0.00363
P6. Surface uniformi~	0.07524
P7. Low weight	0.00318
P8. Self-healing	0.00978
P9. Self-cleaning	0.00523
P10. Strong adhesioi~	0.00505
P11. Transparency	0.00951
P12. Size and Shape	0.08523

As a result, the priorities of the technological capabilities were evaluated (see Tables 5.13 and 5.14). Also, the corresponding paired-wise comparisons are available in Appendix F.

Table 5.13 Technological capabilities priorities.

T1. Nano/microstructured porous material	0.055174
T2. Lubricant-infused surfaces	0.017549
T3. High-conductivity carbon nanotube	0.069944
T4. Powered heating	0.081686
T5. Chemical reaction	0.037822
T6. Ice-phobic carbon nanotube	0.079245
T7. Freezing point depression	0.004901
T8. Anti-freeze proteins' peptides	0.016889
T9. Plasma technology	0.021471
T10. Nanoparticles	0.020297
T11. Gentoo	0.028109
T12. Nanoimprint lithography	0.023277
T13. Self-bonding polymers	0.043635

Table 5.14 Technological capabilities priorities bormalized by cluster.

Name	Normalized by Cluster	Limiting
T1. Nano/microstructured porous material	0.11035	0.055174
T2. Lubricant-infused surfaces	0.03510	0.017549
T3. High-conductivity carbon nanotube	0.13989	0.069944
T4. Powered heating	0.16337	0.081686
T5. Chemical reaction	0.07564	0.037822
T6. Ice-phobic carbon nanotube	0.15849	0.079245
T7. Freezing point depression	0.00980	0.004901
T8. Anti-freeze proteins' peptides	0.03378	0.016889
T9. Plasma technology	0.04294	0.021471
T10. Nanoparticles	0.04059	0.020297
T11. Gentoo	0.05622	0.028109
T12. Nanoimprint lithography	0.04655	0.023277
T13. Self-bonding polymers	0.08727	0.043635

After prioritizing the technological capabilities, the alternatives with considerably more weight were selected for further investigation. Next, the product features addressed by the selected technological capabilities were determined (see Table 5.15).

Table 5.15 Product features addressed by selected technological capabilities.

Technological Capabilities	Product Features											
	P1	**P2**	**P3**	P4	**P5**	**P6**	**P7**	P8	**P9**	P10	P11	**P12**
T1	+	+				+	+		+			+
T2		+							+			
T3	+	+	+		+	+	+					+
T4		+										
T5	+	+			+	+	+	+				+
T6		+				+	+		+			+
T7		+										
T8		+						+				
T9		+					+				+	
T10	+	+										
T11		+	+	+						+		
T12		+		+								
T13		+			+	+				+		+

As the selected technological capabilities would address the product features with the highest weights, T1, T3, T4, and T6 were selected to pursue the process with them. Therefore, their weights were normalized, and the entire model was reduced accordingly (see Table 5.16). Original and reduced models will be illustrated shortly.

Table 5.16 Normalized weight for the technological capabilities of the reduced model.

Technological Capability	**Normalized Weight**
T1	0.192885859
T3	0.244520189
T4	0.285561965
T6	0.277031987

The contribution of each selected technological capability in achieving the product features was also investigated through the limit supermatrix of the ANP model (see Tables 5.17 and 5.18).

Table 5.17 Limit supermatrix of technological capabilities prioritization ANP model (Part I)

Nodes	P1. Compatibility with other chemical layers	P2. ARF	P3. Erosion resistance	P4. Corrosion resistance	P5. Fast dry	P6. Surface uniformity
T1. Nano/microstructured porous material	0.250000	0.068966	0.000000	0.000000	0.000000	0.214286
T2. Lubricant-infused surfaces	0.000000	0.057471	0.000000	0.000000	0.000000	0.000000
T3. High-conductivity carbon nanotube	0.250000	0.114943	0.450000	0.000000	0.600000	0.214286
T4. Powered heating	0.000000	0.287356	0.000000	0.000000	0.000000	0.000000
T5. Chemical reaction	0.250000	0.022989	0.000000	0.000000	0.150000	0.214286
T6. Ice-phobic carbon nanotube	0.000000	0.114943	0.000000	0.000000	0.000000	0.214286
T7. Freezing point depression	0.000000	0.017241	0.000000	0.000000	0.000000	0.000000
T8. Anti-freeze proteins' peptides	0.000000	0.034483	0.000000	0.000000	0.000000	0.000000
T9. Plasma technology	0.000000	0.040230	0.000000	0.000000	0.000000	0.000000
T10. Nanoparticles	0.250000	0.068966	0.000000	0.000000	0.000000	0.000000
T11. Gentoo	0.000000	0.057471	0.550000	0.550000	0.000000	0.000000
T12. Nanoimprint lithography	0.000000	0.068966	0.000000	0.450000	0.000000	0.000000
T13. Self-bonding polymers	0.000000	0.045977	0.000000	0.000000	0.250000	0.142857

Table 5.18 Limit supermatrix of technological capabilities prioritization ANP model (Part II)

Nodes	P7. Low weight	P8. Self-healing	P9. Self-cleaning	P10. Strong adhesioion to the blade (mechanical strength)	P11. Transparency	P12. Size and Shape
T1. Nano/microstructured porous material	0.176471	0.000000	0.348838	0.000000	0.000000	0.193548
T2. Lubricant-infused surfaces	0.000000	0.000000	0.232556	0.000000	0.000000	0.000000
T3. High-conductivity carbon nanotube	0.235294	0.000000	0.000000	0.000000	0.000000	0.161290
T4. Powered heating	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T5. Chemical reaction	0.117647	0.272727	0.000000	0.000000	0.000000	0.129032
T6. Ice-phobic carbon nanotube	0.294118	0.000000	0.418606	0.000000	0.000000	0.322581
T7. Freezing point depression	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T8. Anti-freeze proteins' peptides	0.000000	0.727273	0.000000	0.000000	0.000000	0.000000
T9. Plasma technology	0.176471	0.000000	0.000000	0.000000	1.000000	0.000000
T10. Nanoparticles	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T11. Gentoo	0.000000	0.000000	0.000000	0.500000	0.000000	0.000000
T12. Nanoimprint lithography	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T13. Self-bonding polymers	0.000000	0.000000	0.000000	0.500000	0.000000	0.193548

5.2.6. Transition

In the previous stages, the market drivers, product features, and technological capabilities were identified. Also, the four most contributing technological capabilities were selected. In the subsequent step, efforts were made to develop a solution for integrating the technological capabilities. For this purpose, the Su-Field diagram of the problem was further investigated, and the corresponding standard solutions were determined. As demonstrated in Figure 5.7, the system is categorized as an ineffective complete system in the current state. Therefore, multiple Class 1 and Class 2 standard solutions were discussed to address the problem. Class 1 standard solutions modify a system in order to have the desired outcome or to eliminate an undesired outcome. On the other hand, Class 2 standard solutions make a transition to a more complex Su-Field model to address the problem. The suggested standard solutions were as follows:

Class 1:

1.1. Improving the performance of an inadequate system

1.1.2. The system cannot be changed, but a permanent or temporary **internal additive** is acceptable.

1.1.3. The system cannot be changed, but a permanent or temporary **external additive** is acceptable.

1.1.4. The system cannot be changed, but a **resource from the environment** as the additive can be used.

Class 2:

2.1. Transition to the Complex Su-Field Models

2.1.2. The system can be improved by **adding a second set of substance and field.**

2.2. Forcing the Su-Field Models

2.2.5. The field can be changed from an uncontrolled field to **a field with predetermined patterns.**

2.3. Controlling the frequency to match or mismatch the natural frequency of one or both elements to improve performance

2.3.1. Matching the **frequency** of F and S1 or S2.

2.4. Integrating ferromagnetic material and magnetic fields to improve performance.

2.4.4. Use **capillary** structures.

After considering the selected technologies and the suggested standard solutions, solution 2.1.2 was selected. Therefore, a second set of substance and field was added to the system.

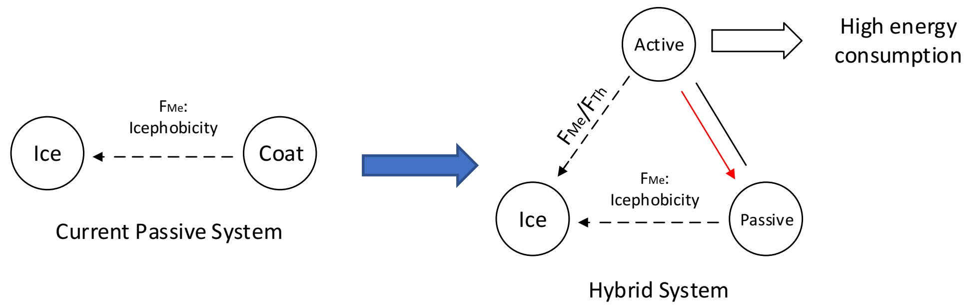


Figure 5.12 Anti-icing system transition Su-Field analysis

In the suggested solution, an active system was combined with the passive coating system. In this scenario, the active system would not be as energy-consuming as having the active system only. Also, the active system would compensate for the gap between the coatings ARF and the ideal ARF through a thermal or mechanical field. In the meantime, the potentially harmful effect of the active system on the passive system must be controlled.

5.2.7. Resources

According to the developing technological capabilities, resources were identified to address the gap between the current states of the alternatives and their required future states. However, the detailed analysis of the gaps between the current level of technological capabilities and their required future level is not within the scope of this research. Table 5.19 shows the identified resources to address the technology gaps.

Table 5.19 Resources to address the gaps in technological capabilities

	Resources	Definition
R1	Chemical engineering	provides a proper chemical combination
R2	Materials engineering	ensures proper adherence to the blades; ensures compatibility between different layers

R3	Nanomaterials engineering	Ensure the proper integration of functional materials at the nanoscale
R4	Mechanical engineering	Ensuring the mechanical integration of the system components
R5	Biotechnology	Ensuring the proper integration of biological systems or living organisms to the system
R6	Ice-phobic coating R&D	Developing an efficient economic ice-phobic coating for helicopter blades

An analysis grid was constructed to investigate how the identified resources contribute to filling the technology gaps. Table 5.20 shows the relationship between the identified resources and technological capabilities. It also highlights the reduced model according to the selected technology alternatives.

Table 5.20 Analysis grid for Technological Capabilities and Resources.

	Technological Capabilities												
Resources	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13
R1	+				+	+	+		+	+	+	+	+
R2	+	+									+	+	+
R3	+		+			+						+	
R4		+	+	+					+			+	
R5								+					
R6	+	+	+	+	+	+	+	+	+	+	+	+	+

The resources needed to be prioritized to facilitate budget and organizational resource planning. Figure 5.13 illustrates the original ANP model for prioritizing the resources. However, the model was reduced to the resources addressing the selected technological capabilities (see Figure 5.14 and 5.15).

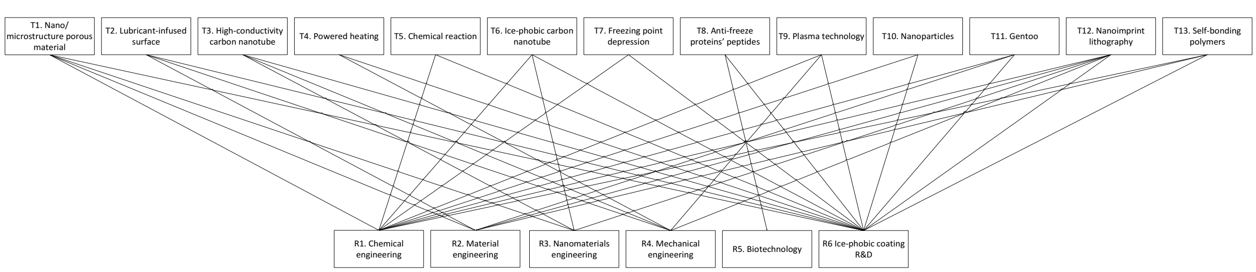


Figure 5.13 ANP model for prioritization of resources.

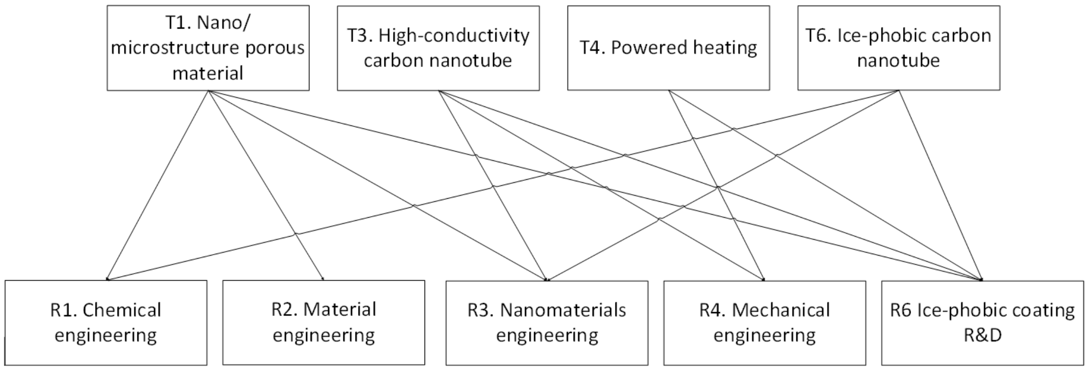


Figure 5.14 Reduced ANP model for prioritization of resources.

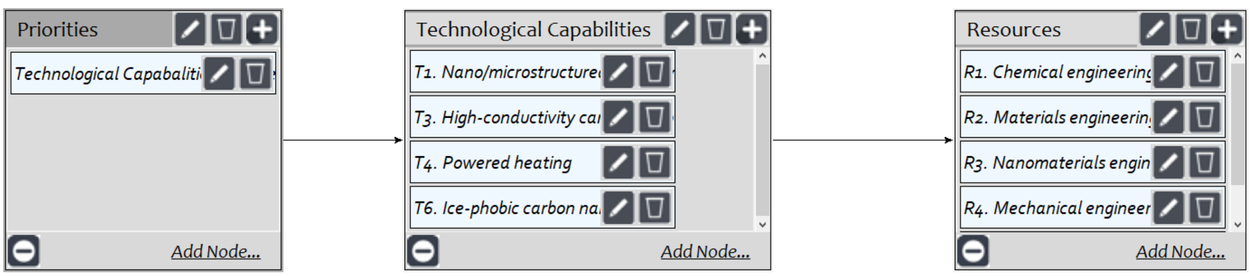


Figure 5.15 Reduced ANP model for prioritization of resources in SuperDecision software.

Table 5.21 shows the criteria weights for technological capabilities derived from the previous ANP model.

Table 5.21 Criteria weights for Resources-Technological Capabilities ANP model.

Graphical | Verbal | Matrix | Questionnaire | Direct

T1. Nano/microstruct~	0.19289
T3. High-conductivit~	0.24452
T4. Powered heating	0.28556
T6. Ice-phobic carbo~	0.27703

According to the status of the technological capabilities in Table 5.10, some of the technological capabilities are already existing, while some of them are still being developed. Therefore, the amount of resources required for addressing their gaps is not equal. Hence, a mutually accepted correction factor was applied to the technological capabilities weights for resource requirements. In this correction factor, the developing technologies' resource requirement is three times more than the resource requirement of existing technologies (see Figure 5.16 and Table 5.22).

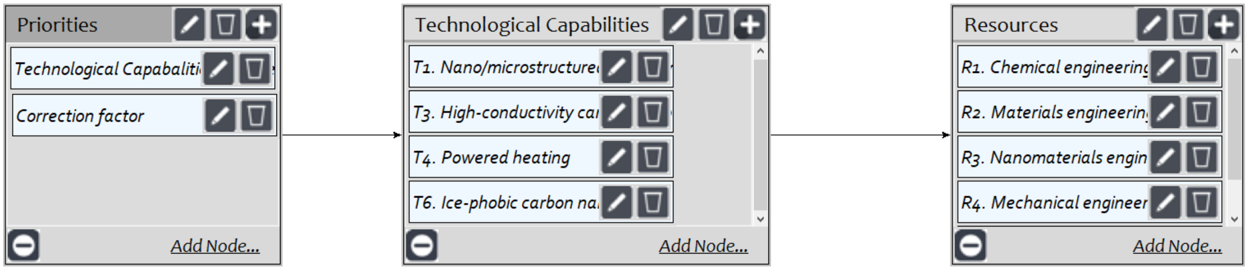


Figure 5.16 Reduced ANP model for prioritization of resources with correction factor in SuperDecision software.

Table 5.22 Correction factor for technological capabilities weights.

Graphical | Verbal | Matrix | Questionnaire | Direct

T1. Nano/microstruct~	4
T3. High-conductivit~	4
T4. Powered heating	1
T6. Ice-phobic carbo~	4

Finally, the resources were prioritized as the result of the ANP analysis. Table 5.23 shows the resources priorities. Also, the corresponding paired-wise comparisons are available in Appendix F.

Table 5.23 Resources priorities normalized by cluster.

Name	Normalized by Cluster	Limiting
R1. Chemical engineering	0.20875	0.104377
R2. Materials engineering	0.06257	0.031286
R3. Nanomaterials engineering	0.30079	0.150394
R4. Mechanical engineering	0.18266	0.091328
R6. Ice-phobic coating R&D	0.24523	0.122614

As discussed, the roadmap was reduced after selecting the four most contributing technological capabilities. Of course, the reduction in technology level will result in a reduction in other layers following the dependencies. However, after the reduction in technology, resource, and product layer, no market driver was compromised. Appendix E, Figure E.1 and E.2 illustrate the original universal ANP model and the reduced universal ANP model of the problem, respectively.

5.3. Risk Analysis

5.3.1. Constructing the network

After coming up with the reduced model, it was time to consider the uncertainty of each node. Therefore, the model was turned into a Bayesian Network. However, the within-layer relationships have been removed for model simplification. Appendix E, Figure E.3 illustrates the Bayesian Network of the reduced model.

5.3.2. Assigning probability distributions

After constructing the network, probability distributions were assigned to each node to reflect the dependencies and intrinsic risks. The success probabilities represent the probability of the note to be developed or met within the planned timeframe. However, the process of deciding about the desired timeframes is not within the scope of this research. Appendix E, Figure E.4 illustrates the probabilistic network before considering the risk factors.

5.3.3. Non-intrinsic risks identification

At this point, four non-intrinsic risks were identified, which are shown in Table 5.24.

Table 5.24 Non-intrinsic risk factors

	Risk Factors	Impact	Definition
RF1	Only passive system policy	Negative	The proposed solution incorporated both passive and active systems. Although the hybrid approach is adopted, the company might change its policy and decide to develop only a passive system and eliminate the active systems.
RF2	Nanotechnology breakthrough	Positive	Considering the recent advancements in nanotechnology, there is a good chance of a breakthrough in the nanotechnology area leading to enormous advancement in the corresponding technological capabilities
RF3	Environmental side-effects	Negative	The potentially harmful impact of nanomaterials on the environment can lead to restriction of using particular materials in products
RF4	Change of company policy	Negative	The company might decide to reduce the budget for ice-phobic coating R&D

Table 5.25 shows how the risk factors affect the resources R3 and R6 and the technological capability T4.

Table 5.25 Analysis grid for Risk Factors and Affected Nodes

		Affected Nodes		
		R3	R6	T4
Risk Factors	RF1			-
	RF2	+		
	RF3	-		
	RF4		-	

Appendix E, Figure E.5 shows the Bayesian Network considering the risk factors.

5.3.4. Vectorized Bayesian Network

Once the Bayesian Network was developed, the weight vectors were calculated based on the algorithm demonstrated in chapter 3, section 7.

Market drivers weight vector:

$$W_D = [0.001904 \quad 0.00596 \quad 0.005628 \quad 0.018594 \quad 0.012844 \quad 0.01539 \quad 0.123774 \quad 0.253374]$$

Therefore, Table 5.26 shows the weight vectors for the product features.

Table 5.26 Product features weight vectors

	D1	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**
W_D	0.00190404	0.00596	0.005628	0.018594	0.012844	0.01539	0.123774	0.253374
W_{P1}	-	0.004947	0.004559	-	-	-	-	-
W_{P2}	-	-		-	-	-	-	0.228036
W_{P3}	-	-		0.016734	-	-	-	-
W_{P5}	-	-	0.00484	-	-	-	-	-
W_{P6}	-	-		-	-	0.013236	0.107684	-
W_{P7}	0.0016946	0.005185	0.00484	-	-	-	-	-
W_{P9}	-	-	-	0.015247	0.010917	-	-	-
W_{P12}	0.00173268	0.005185	0.004897	-	-	0.013236	0.107684	-

Also, Table 5.27 shows the weight vectors for the technological capabilities.

Table 5.27 Technological capabilities weight vectors

	D1	D2	D3	D4	D5	D6	D7	D8
W_{T1}	0.00281036	0.011029	0.010436	0.01113	0.008625	0.020912	0.174448	0.180149
W_{T3}	0.00281036	0.011182	0.016457	0.014391	0	0.020648	0.157218	0.177868
W_{T4}	0	0	0	0	0	0	0	0.168747
W_{T6}	0.00270754	0.007882	0.007595	0.011892	0.008843	0.021442	0.183062	0.184709

Next, the weight vectors were calculated for the resources (see Table 5.28).

Table 5.28 Resources weight vectors

	D1	D2	D3	D4	D5	D6	D7	D8
W_{R1}	0.00427861	0.01603	0.014997	0.019754	0.014144	0.033047	0.268865	0.263427
W_{R2}	0.00216604	0.0098	0.009144	0.00988	0.007074	0.01673	0.136112	0.131349
W_{R3}	0.00394753	0.014906	0.013944	0.018217	0.013044	0.03049	0.24806	0.242904
W_{R4}	0.00451989	0.017166	0.019636	0.022744	0.007424	0.03491	0.284027	0.281807
W_{R6}	0.00772096	0.031071	0.033034	0.037607	0.017035	0.059635	0.48518	0.638593

Finally, Table 5.29 shows the weight vectors for the risk factors.

Table 5.29 Risk factors weight vectors (×1000)

	D1	D2	D3	D4	D5	D6	D7	D8
W_{RF1}	0	0	0	0	0	0	0	0.37444
W_{RF2}	0.552654	2.0868898	1.952136	2.550348	1.826148	4.268553	34.72845	34.00659
W_{RF3}	0.005234	0.02552	0.025448	0.041677	0.015283	4.031429	0.355555	0.307851
W_{RF4}	0.001316	0.00679	0.007226	0.00886	0.002819	1.013781	0.089411	0.109765

The evaluated weight vectors provided us with information about the contribution of each network node in meeting the ultimate market drivers. They were also used in scenario analysis.

5.3.5. Scenario Analysis

Two scenarios were chosen to be analyzed based on their potential impact on the most important market drivers D7 and D8.

$$W_D = [0.001904 \quad 0.00596 \quad 0.005628 \quad 0.018594 \quad 0.012844 \quad 0.01539 \quad \mathbf{0.123774} \quad \mathbf{0.253374}]$$

Scenario #1: RF1 occurrence

By referring to the weight vector of RF1, we can see that the only market driver affected by RF1 is D8:

	D1	D2	D3	D4	D5	D6	D7	D8
W_{RF1}	0	0	0	0	0	0	0	**0.100085**

However, according to the weight vector of the market drivers, we will figure out that D8 happens to be the most important market driver.

$$W_D = [0.001904 \quad 0.00596 \quad 0.005628 \quad 0.018594 \quad 0.012844 \quad 0.01539 \quad 0.123774 \quad \mathbf{0.253374}]$$

Therefore, the RF1 occurrence scenario was simulated by changing the RF1 node to a piece of evidence by setting its probability distribution to 100% **Yes**. According to the updated conditional probabilities, given the occurrence of RF1, T4 would be completely compromised. Therefore, it would result in a drastic decrease in the success probability of P2 from 79% to 57%. Moreover, the probability of successfully meeting the market driver D8 would reduce from 87% to 73% (see Appendix E, Figure E.6).

Therefore, it became clear that in the event of a change in policy about developing a hybrid system, the technologies addressing the passive system cannot compensate for the loss in the probability of meeting D8 in time. At this point, the weight vector of T4 was investigated:

	D1	D2	D3	D4	D5	D6	D7	D8
W_{T4}	0	0	0	0	0	0	0	0.168747

It was concluded that had RF1 occurred, T4 must be replaced with a technological capability having almost the same contribution to meeting D8 as T4. Alternatively, the other technologies involved should compensate by increasing the D8 element in their weight vector. As the weight of the product features remains the same, the compensation must increase the success probability of the other technological capabilities, which will require more resources. The required compensations to meet D8 in time despite RF1 occurrence can be seen in Appendix E, Figure E.7, in which D8 is also assured through changing its node to a piece of evidence.

Scenario #2: RF2 occurrence

The other simulated scenario was the occurrence of RF2 due to its considerable impact on market drivers D7 and D8. In other words, a breakthrough in nanotechnology would be a great help in developing an ice-phobic coating solution. Therefore, this risk factor is considered a positive element.

	D1	D2	D3	D4	D5	D6	D7	D8
W_{RF2}	0.552654	2.0868898	1.952136	2.550348	1.826148	4.268553	**34.72845**	**34.00659**

Meanwhile, according to the weight vector of the market drivers, the market drivers D7 and D8 are the most important market driver.

$$W_D = [0.001904 \quad 0.00596 \quad 0.005628 \quad 0.018594 \quad 0.012844 \quad 0.01539 \quad \mathbf{0.123774} \quad \mathbf{0.253374}]$$

Therefore, the scenario of RF2 occurrence was also simulated the same way. According to the updated conditional probabilities, given the occurrence of RF2, the probability of R3 will be drastically increased from 60% to 82%. Then, T1 was increased from 64% to 71%. Next, T3 was increased from 63% to 73%. Finally, T6 was increased from 68% to 75%.

By referring to the technological capabilities weight vectors, we can see that T1, T3, and T6 play important roles in meeting the market drivers D7 and D8.

	D1	D2	D3	D4	D5	D6	D7	D8
W_{T1}	0.00281036	0.011029	0.010436	0.01113	0.008625	0.020912	**0.174448**	**0.180149**
W_{T3}	0.00281036	0.011182	0.016457	0.014391	0	0.020648	**0.157218**	**0.177868**
W_{T6}	0.00270754	0.007882	0.007595	0.011892	0.008843	0.021442	**0.183062**	**0.184709**

Therefore, following the increase in the probability of multiple product features, D7 increased from 85% to 88%, and D8 increased from 87% to 89% (see Appendix E, Figure E.8).

Finally, Figure 5.17 illustrates the ultimate first version of the technology roadmap.

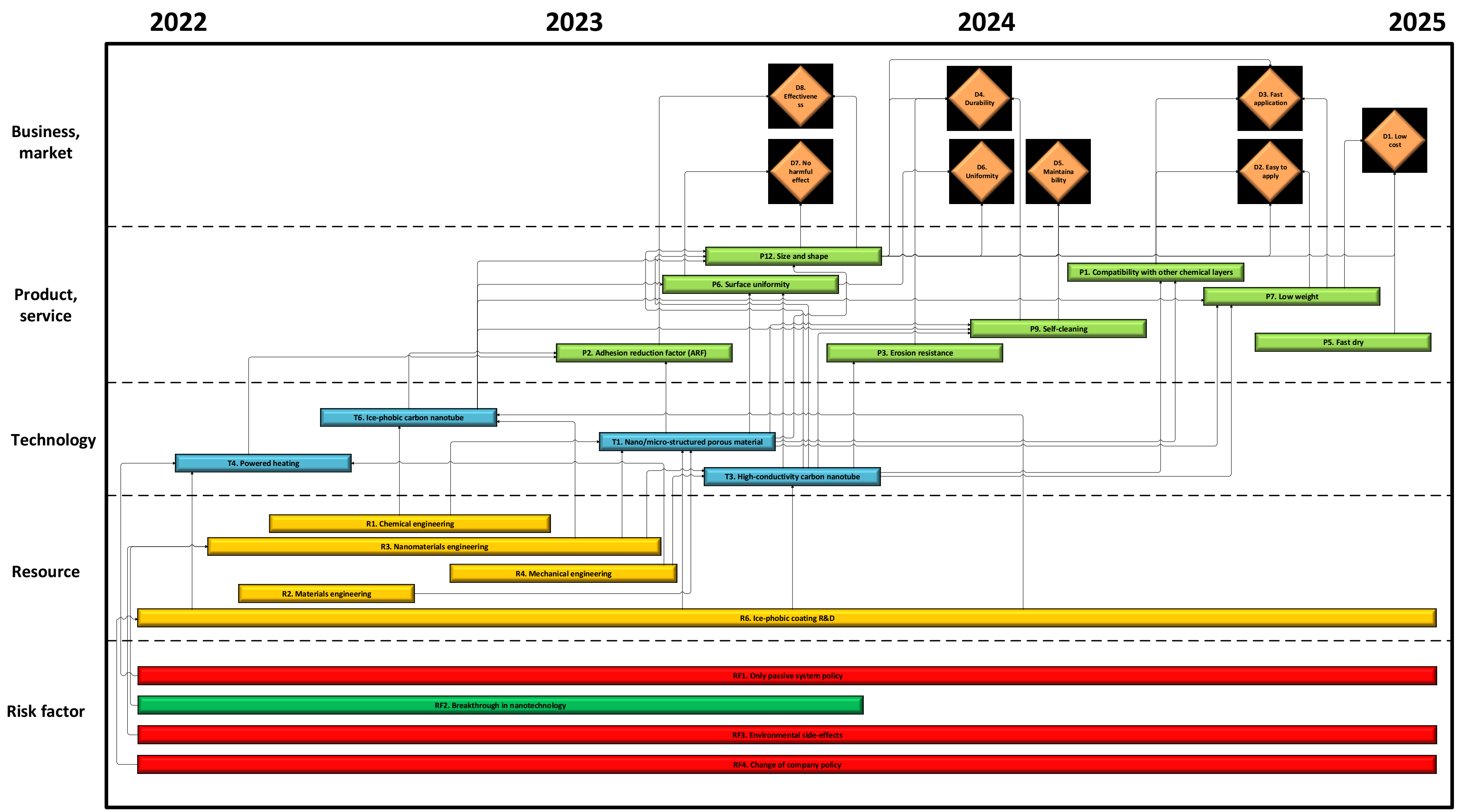


Figure 5.17 First version of the technology roadmap

Chapter 6

Discussion and Conclusions

Following the results chapter, chapter 6 will discuss the interpretations of the results. Also, it will demonstrate why the results are essential and will be helpful to a company. Moreover, the limitations of the approach and results will be discussed. Finally, recommendations will be made for practical actions and further scientific studies.

6.1. Introduction

The final roadmap was charted based on the timeframe suggested by the experts, and the dependencies were determined on it. Also, the order of addressing the elements was based on each element's importance and the prerequisite dependencies. The ultimate result of the case study showed that within the planned timeframe, the success probability of neither of the market drivers exceeds 90%. Whether this success probability is acceptable or not depends on the company and its policies. Nevertheless, to increase the success probability, multiple strategies can be adopted. Of course, the most straightforward approach is to extend the timeframe. However, extending the timeframe might not be an option in highly competitive environments. In that case, fundamental changes and improvements might be necessary for the inner layers of the roadmap to improve the success probabilities while keeping the same deadlines. In the meantime, two scenarios were simulated for the developed roadmap. Each risk occurrence scenario showed the consequence and the impact of each risk event on the roadmap elements and market drivers. Thus, adaptive action plans were discussed to adapt to the situation.

6.2. Interpretations

As explained in chapter 1, this research followed three objectives. The first objective was strengthening the linkage between market drivers and technological capabilities in exploratory and technology-oriented roadmaps to have a balanced market-pull and technology-push strategy. In the conducted case study, the roadmap was developed for a state-of-the-art technology to address a struggling problem. As no practical technology has been developed before to address the same problem the same way, the nature of this roadmap was exploratory. Therefore, many angles had to be considered, which had minimal literature available. Therefore, the roadmapping experts had no choice but to explore new areas and opportunities. TRIZ was a beneficial tool used to address the exploratory nature of the developed roadmap. It helped the team to go through alternative solutions exhaustively and choose the most practical one.

In the meantime, the linkage between the market drivers and technology drivers was strengthened by applying an enhanced T-plan. Although due to the intensive desire of the market for an ice-phobic coating solution, the market-pull strategy does not seem challenging, identifying the right market drivers to address was a big challenge. On the other hand, certain technological capabilities had to be selected to be pushed to the market, addressing the proper market drivers. Therefore, it was necessary to have a balance between market-pull and technology-push strategy. The enhanced T-plan was a crucial response to this necessary need. The enhanced T-plan method reduced the model in the stage of technological capability identification based on multiple decision-making processes to assure the right market drivers will be addressed optimally. This approach led to selecting specific technological capabilities to be pushed to the market while not compromising any market driver. Therefore, the adopted strategy managed the technologies pushed to the market while considering the market demands properly.

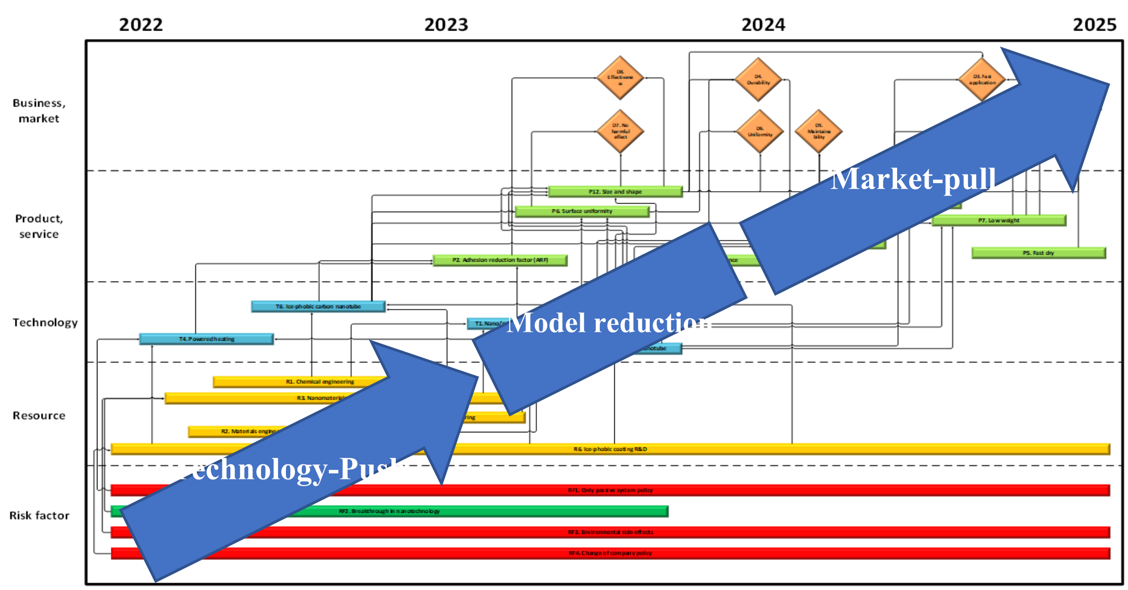


Figure 6.1 Market-pull and Technology-push balance strategy

The second objective of the research was developing a robust TRM process through quantitative analysis and decision-making means. The TRM literature highlights the lack of reliability and objectivity of the roadmapping process as one of its most significant limitations. Whereas the enhanced T-plan successfully incorporated multiple quantitative analysis methods for decision-making and risk analysis of TRM to minimize the objectivity and increase the reliability of the process. Another significant limitation of the roadmapping process was its lack of standardization. Therefore, companies had no choice but to reinvent the entire process each time there were to apply roadmapping. While the proposed enhanced T-plan process also addressed this limitation. The enhanced T-plan is a robust process model that can be applied in different contexts, fields, and industries. Therefore, in the case study, all the steps were taken based on the proposed process model. Therefore, the drivers of each layer were methodologically clustered, weighted, and translated to the drivers of the next layer. In the end, and to address the third objective of the research, the intrinsic and non-intrinsic risks were identified. Thus, a probabilistic model of the roadmap was developed by using a Vectorized Bayesian Network. Therefore, different scenarios were simulated, and corresponding adaptive actions were discussed. Finally, the process ended with charting the first version of the technology roadmap. This entire process can be repeated in different contexts and to address different problems.

6.3. Implications

While the results of this research agree with the previous studies on the applications and benefits of TRM, they also add new insights and techniques to different angles of the context. Thus, this research contributes to the literature of TRM in four main aspects:

- **Hybrid logistics:** The literature highlighted the importance of establishing a balance between market-pull and technology-push strategies; however, it lacked a practical method for establishing it. The proposed framework addresses this issue by reducing the model based on the priorities and weights of the elements depending on the roadmap's goal.

- **Reliability and objectivity:** The quantitative analysis techniques incorporated in the proposed framework minimize the subjectivity of the roadmap. The experts' opinions are analyzed through numerical models free from bias so that the outcomes will be reliable and practical. Moreover, lab tests can be involved in different stages of the process to maximize the reliability and objectivity of the roadmap.

- **Standardization:** The literature highlights that a significant downside of TRM is the lack of a standard process. Because of this issue, companies and organizations have to reinvent the entire process every time it needs to be applied. Moreover, many companies quit applying TRM in the initial steps due to the lack of guidelines and general instructions. Therefore, this research tried to develop a standard, repeatable process model for TRM introduced as the enhanced T-plan consisted of six workshops.

- **Adaptive risk assessment:** Roadmapping in an uncertain environment has attracted much attention during the last couple of years and is becoming a research trend. The main reason is that uncertainties highly influence the business environments, and for the roadmaps to be practical, these uncertainties must be taken into account. There have been efforts to analyze the consequences of the risk events threatening the elements of a roadmap; however, they mostly lack a practical method to address the potential impact of a risk event on the elements, especially the market drivers. The proposed framework suggests a practical numerical method to investigate the risk events' consequences and impacts through a Vectorized Bayesian Network. It also allows simulating different scenarios and investigating the circumstances under the influence of risk events or any other evidence.

6.4. Limitations

The limitations of this research can be summarized in two categories. The first category is the limitations concerning the case study, and the second category is the limitations concerning the proposed framework:

Case study limitations

As mentioned in the methodology chapter, the most important limitation of the case study was the lack of accurate data. The data collection process was highly impacted by the 2020-2021

COVID19 crisis and the global pandemic. During the time of this study, the involved companies and organizations were working remotely and with their minimum possible capacity. Therefore, industry experts were either unavailable or extremely busy with the overload due to the circumstances. Therefore, the study could not be adequately accommodated by the industry experts.

Moreover, due to the nature of TRM, multiple disciplines and science fields were involved in the case study. Therefore, Bell Textron did not have the experts for many fields available in their R&D unit. In fact, in the previous attempts to develop an ice-phobic coating, many aspects of the R&D were outsourced to third-party companies. Of course, involving the experts from the third-party company would be a great help for this study. However, it was not an option as the contract between Bell Textron and the third-party companies was terminated. In the end, despite the lack of expert knowledge, the qualitative data was adequately collected from the literature. However, the reliability of the case study result is impacted by the inaccuracy of the quantitative data input.

Meanwhile, the inaccuracy of the data does not undermine the validity of the process model as it relies on the literature and numerous previous studies. Had the circumstances been ordinary, the case study could involve an adequate number of experts and follow the six-workshop enhanced T-plan framework. In that case, the results would be reliable and could be taken into action in the real world.

Framework limitations

When the model is being reduced at the stage of technological capability selection, the reduction takes place based on the priority and importance of the technology drivers. The limitation of the framework is that when prioritizing the technology drivers, the feasibility of developing them within the timeframe is not taken into account. For instance, assuming that a particular product feature has a high priority, the technological capability addressing that feature will have a high priority as a result. However, that technological capability's feasibility (success probability) is not considered a criterion for model reduction at that point. The model will be reduced first, and then, the success probability of the elements of the reduced model will be investigated. On the contrary, suppose the feasibility was considered as a criterion when prioritizing the technological capabilities. In that case, the priorities might have been different, resulting in a different reduced model and, therefore, an entirely different roadmap and strategic plan.

On the other hand, the experts cannot accurately estimate the success probability of a technological capability unless they have a clear idea about the number and amount of resources allocated to that. Meanwhile, to have an idea about the resource allocation to a technological capability, the addressing technological capabilities must be already selected. Therefore, the model deals with a loop that must be addressed. Although the model reduction took place in the technology layer in the case study due to the technology-oriented nature of the case, the explained loop can appear in any layer in which the model reduction is taking place.

In the meantime, if there are limited technological capability options for addressing a product feature, even a low feasibility technology driver might be the best shot for addressing a product feature. In those cases, there might be no choice but to plan on developing a technological capability with a low success probability. Of course, theoretically, the timeframes can be extended as well; however, this approach is not always very practical.

In addition, another limitation of the framework is its extensive reliance on the experts' opinions. Although the proposed framework incorporated multiple techniques to get the best unbiased opinions for the industry experts, the logistics of gathering a considerable number of experts from different industries and disciplines makes the process very complex.

6.5. Recommendations for further studies

This research suggests four research paths to address the above-mentioned limitations and further important angles of the topic:

1. **Feasibility as prioritization criteria:** As discussed, it seems necessary to involve the feasibility of a network node in the criteria for decision-making about nodes' priorities. However, the estimation of the success probability of the node will not be accurate if the model is not reduced yet, and the resource allocation is not yet clear. For addressing this contradiction, an iterative algorithm can be developed to investigate the different

combinations of driver selection and improve the accuracy of the estimation about the feasibility of a driver and include that as a prioritization criterion.

2. **Optimization:** In an attempt to reduce the involvement of experts in the process -especially in multiple stages of decision making- an optimization algorithm can be developed to decide about the optimal reduced model considering the priorities, weights, and probabilities of the nodes.

3. **Sub-layers:** Incorporating the Analytic Network Process (ANP) and considering its advantages over Analytic Hierarchy Process, along with Vectorized Bayesian Network, this research showed that the drivers belonging to the same layer could have within-layer relationships and even prerequisite dependencies. Although this research neglected the within-layer dependencies to avoid overcomplexity at this stage, sub-layers can be introduced in the roadmap to investigate these relationships and dependencies further.

4. **Time-based revisions:** Of course, in reality, the uncertainty (all the probabilities and even weight vectors of the network are) is a function of time and multiple environmental factors. Therefore, as time goes by, the attributes of the network nodes change, and the roadmap might require to be modified accordingly. Therefore, certain milestones need to be set for a time-based follow-up and revision of the roadmap. These important steps can be annexed to the enhanced T-plan framework to supplement standard guidelines for TRM.

5. **Sensitivity analysis:** A company might decide to increase the budget for the roadmap goal. However, they have to decide about where to allocate the additional budget. In that situation, sensitivity analysis can be conducted on the Vectorized Bayesian Network to figure the best technology to invest in further.

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Appendix A

Technology Roadmapping Tables and Figures

Table A. 1 Number of publications per journal and per year. Note: Journals are listed in descending order of publications related to roadmapping. Adopted from Carvalho et al. (2013).

Journal	Year															
	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Total
Technological Forecasting and Social Change					1			8	1			1	6	4	1	22
Research-Technology Management	1						5	5			3	2	1	1		18
International Journal of Technology Management								1					2			3
R & D Management								1				2				3
Technovation										1	1				1	3
DYNA														2		2
IEEE Transactions on Engineering Management					1			1								2
Journal of Cleaner Production									1	1						2
Journal of Engineering and Technology Management															2	2
Journal of Systems Science and Systems Engineering											1		1			2
BT Technology Journal									1							1
Canadian Journal of Civil Engineering													1			1
Energy Policy										1						1
Engineering Management Journal											1					1
IEEE Aerospace and Electronic Systems Magazine								1								1
IEEE Robotics & Automation Magazine									1							1
IEEE Transactions on Components and Packaging Technologies									1							1
IEEE Transactions on Medical Imaging												1				1
International Journal of Computer Integrated Manufacturing												1				1
International Journal of Service Industry Management												1				1
Journal of Lightware Technology								1								1
Journal of Neuroimagin															1	1
Journal of Product Innovation Management					1											1
Journal of Systems and Software															1	1
Proceedings of the institution of mechanical engineers part B							1									1
Production Planning & Control									1							1
Revista Ingeriana e Investigation												1				1
Systems Research na Behavioral Science										1						1
Technology Analysis & Strategic Management														1		1
Technology Management in the Age of Fundamental Change													1			1
Total	1	0	0	0	3	0	6	18	6	4	6	9	12	8	6	79

Table A. 2 Publications by period showing the level of analysis and the methodological approach. Adopted from Carvalho et al. (2013)

	Period					
Level of Analysis	1997 - 2001	2002 - 2006	Tendency	2007 - 2011	Tendency	Total
LA1 - Strategy & Business Level	2	17	↗	19	↗	38
LA2 - Innovation & NPD Level	2	17	↗	22	↗	41
Total	4	34		41		79
Method						
CR1: Literature review	2	8	↗	6	↘	16
CR2: Simulation or theoretical modeling	0	0		2	↗	2
ER1: Survey	0	3	↗	4	↗	7
ER2: Case study	2	23	↗	28	↗	53
ER3: Action research	0	0	-	1	↗	1
Total	4	34		41		79

Table A. 3 Limitations of the roadmap. Adopted from Carvalho et al. (2013)

	Abe et al. (2009)	Amadi et al. (2011)	Amer and Daim (2010)	Daim and Oliver (2008)	Dissel et al. (2009)	Elliott (2005)	Fenwick et al. (2009)	Galvin (2004)	Groenveld (1997)	Grossman (2004)	Kostoff et al. (2004)	Lee and Park (2005)	Lee et al (2009a)	McCarthy (2003)	McMillan (2003)	Probert and Radnor (2003)	Saritas and Aylen (2010)	Talonen and Hakkarainen (2008)	Wall et al. (2005)	Total
LIMITATIONS																				
Are normative, more than exploratory																	x			1
Difficult to disseminate																	x			1
Difficult to evaluate business value	x																			1
Difficult to express a business attractiveness of R&D outputs	x																			1
Difficult to express a business system or operation model	x																			1
Difficult to customizing												x								1
Encourages linear and isolated thinking																	x			1
Provides little guidelines													x							1
Lacks focus and clear boundaries							x													1
Lacks reliability and objectivity													x							1

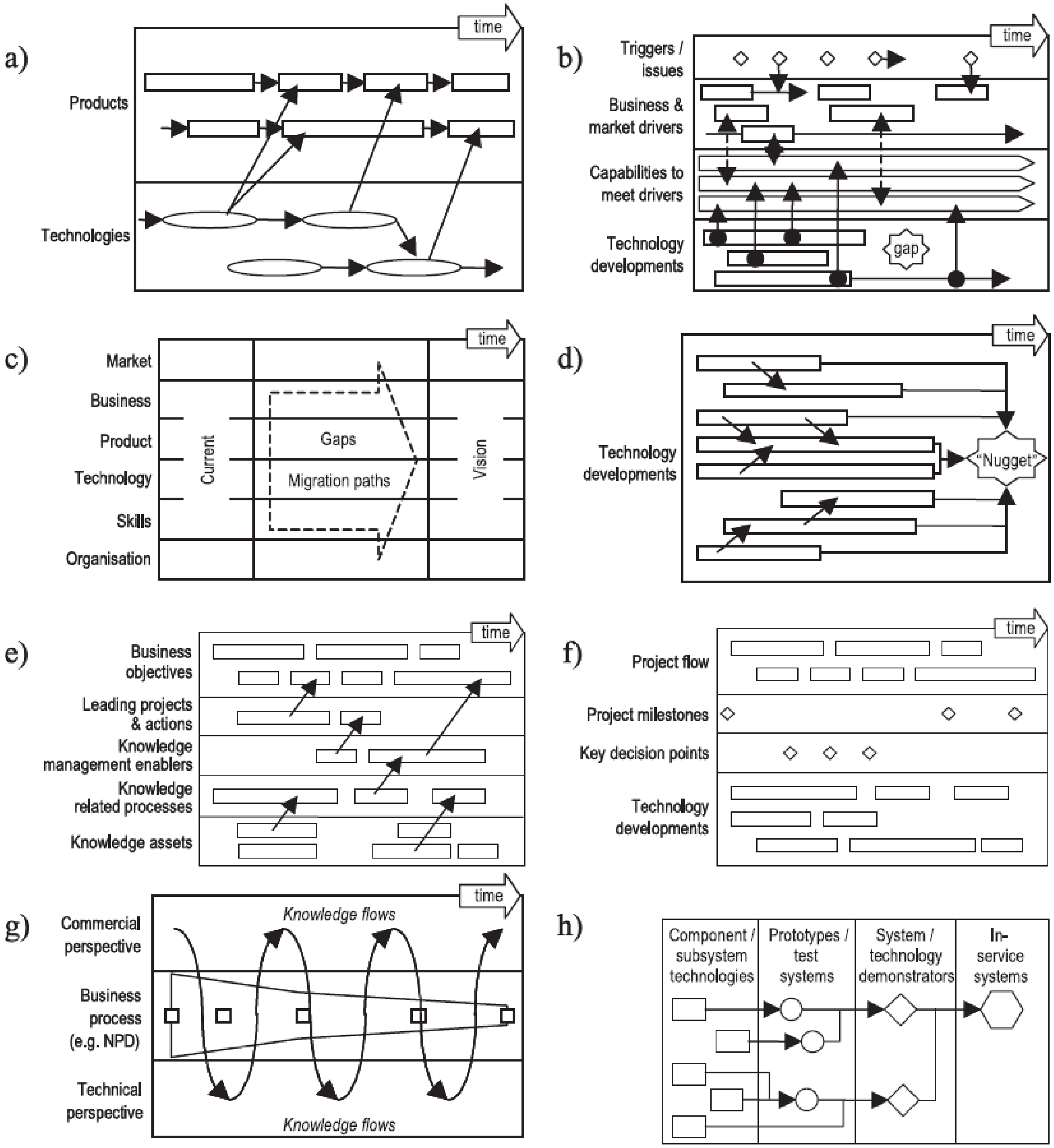


Figure A. 1 Examples of technology roadmap types (purpose): (a) product planning [122]; (b) service/capability planning [121]; (c) strategic planning; (d) long-range planning [119]; (e) knowledge asset planning [111]; (f) program planning [34]; (g) process planning; (h) integration planning [113].

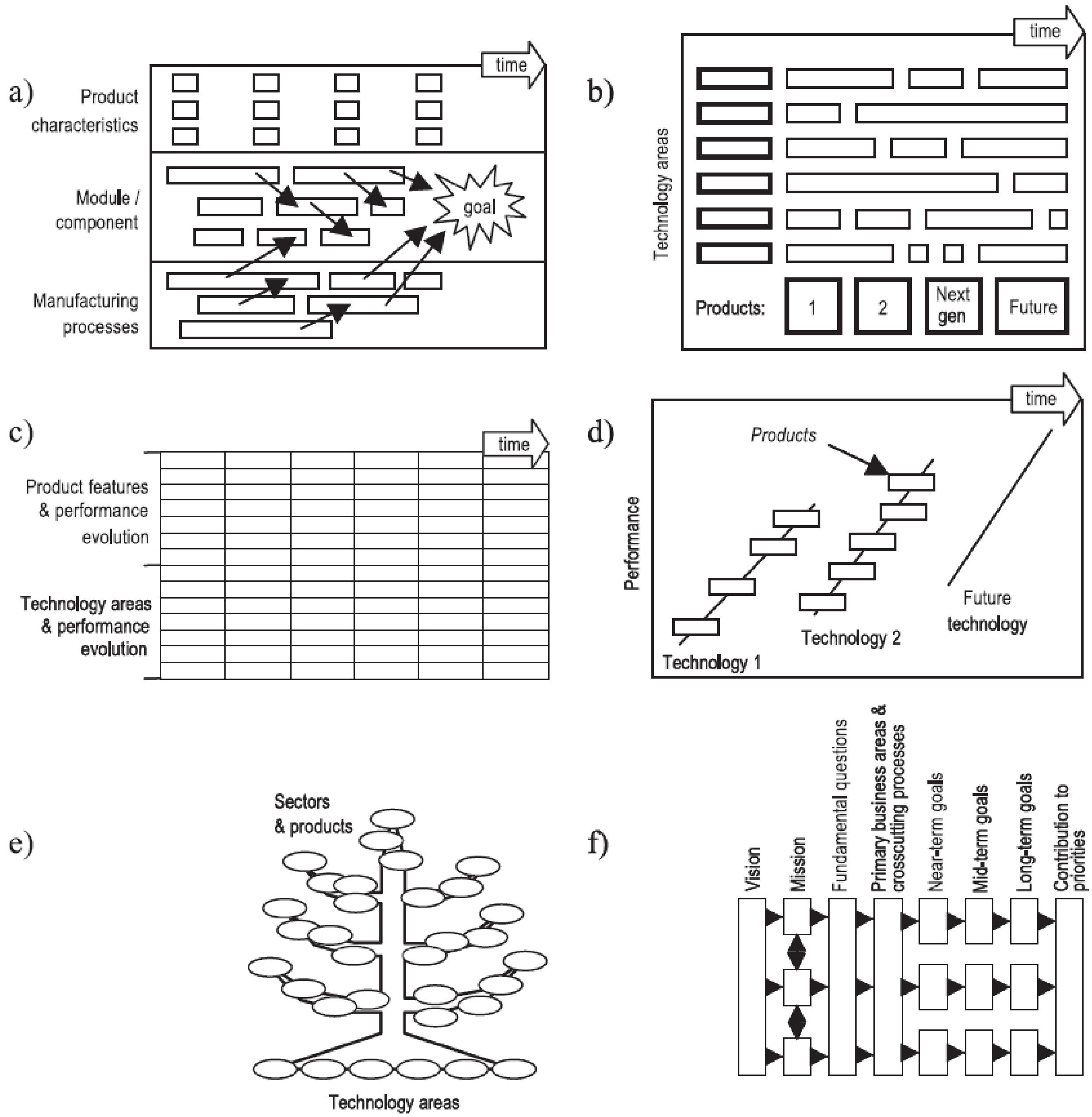
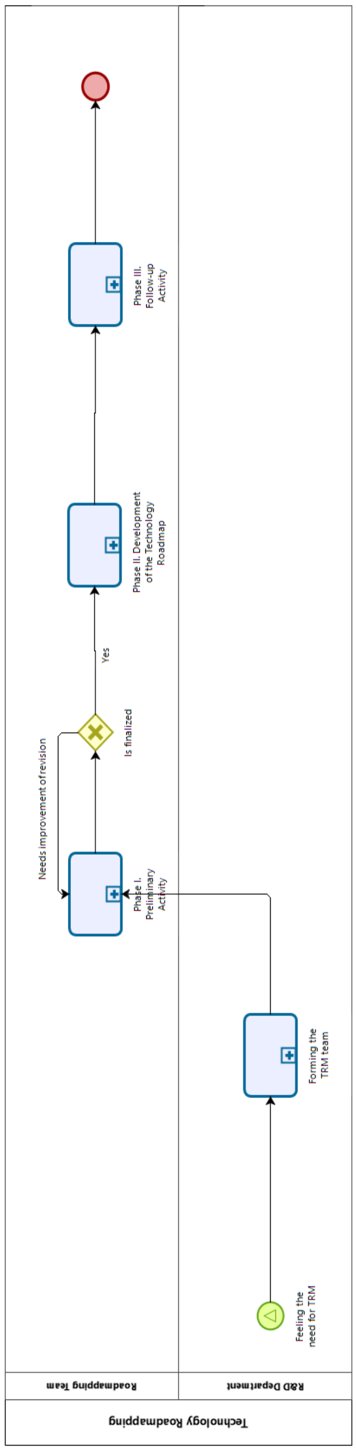


Figure A. 2 Examples of technology roadmap types (format): (a) multiple layer [32]; (b) bars [57]; (c) tabular [30]; (d) graphical [30]; (e) pictorial [58]; (f) flow chart [59].



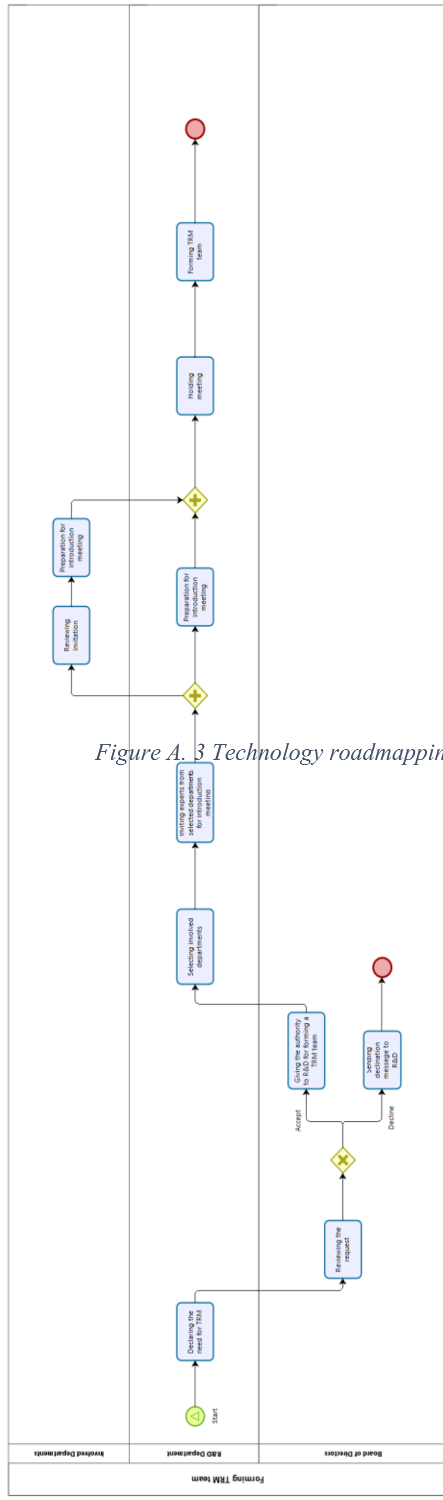


Figure A. 3 Technology roadmapping, forming TRM team BPMN model.

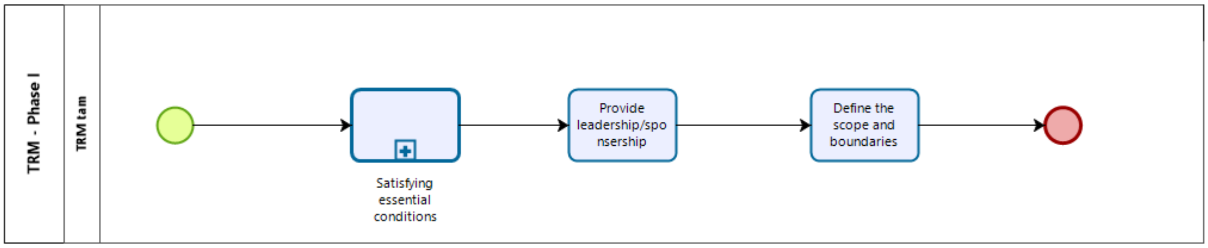


Figure A. 4 TRM Phase I BPMN model

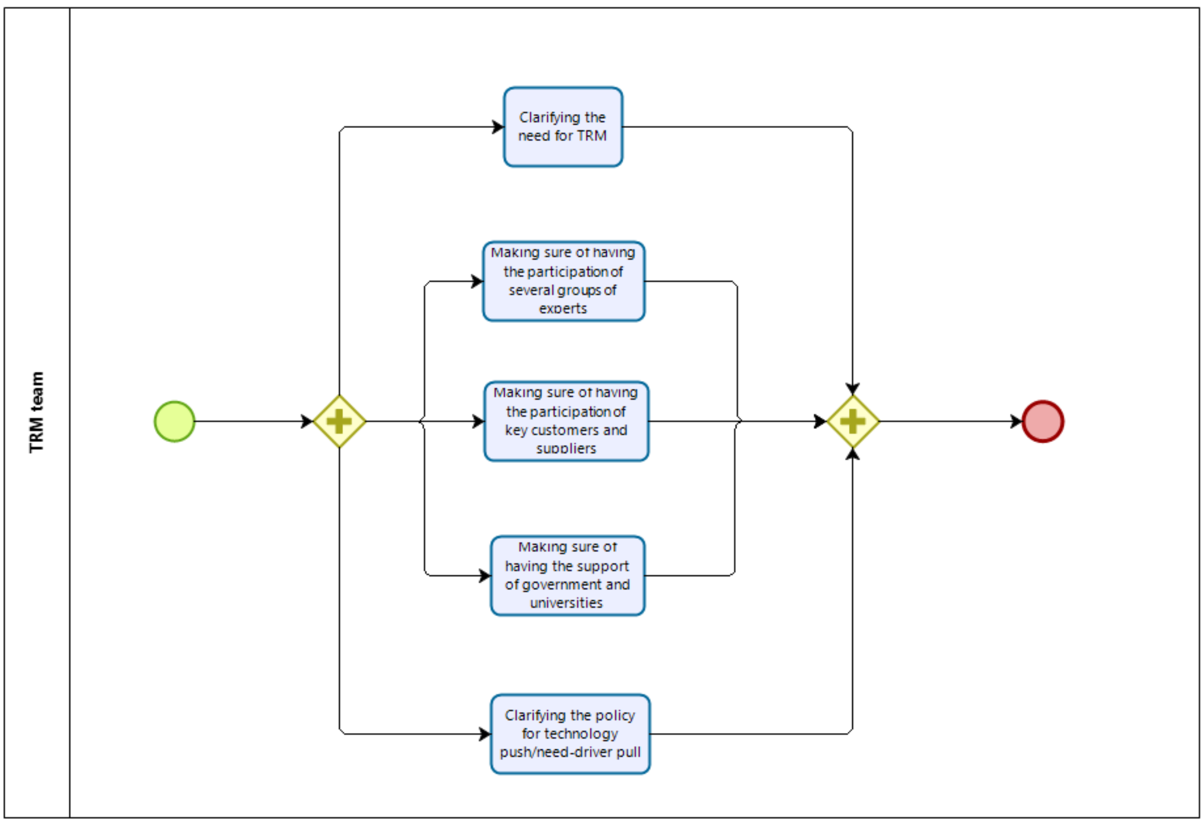


Figure A. 5 TRM Phase I, satisfying essential conditions BPMN model.

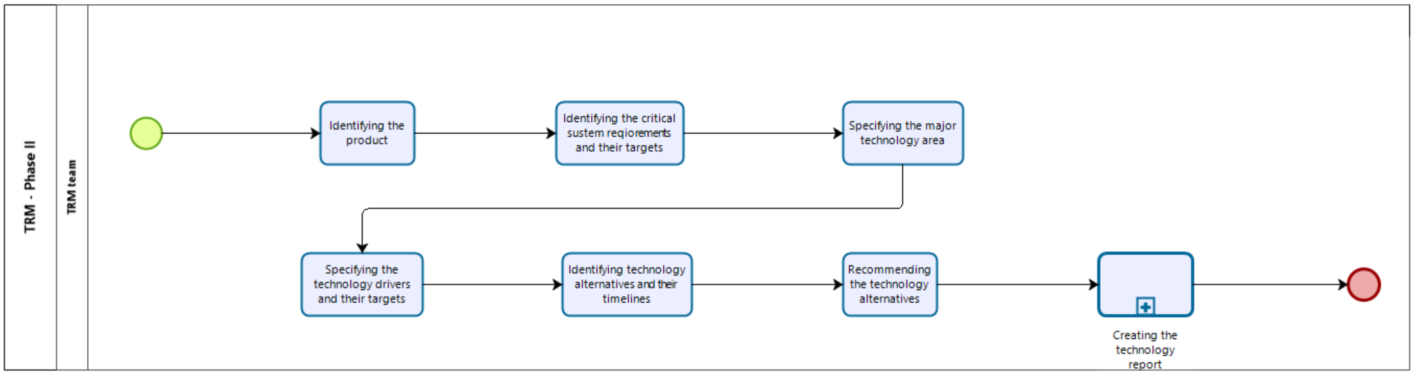


Figure A. 6 TRM Phase II BPMN model.

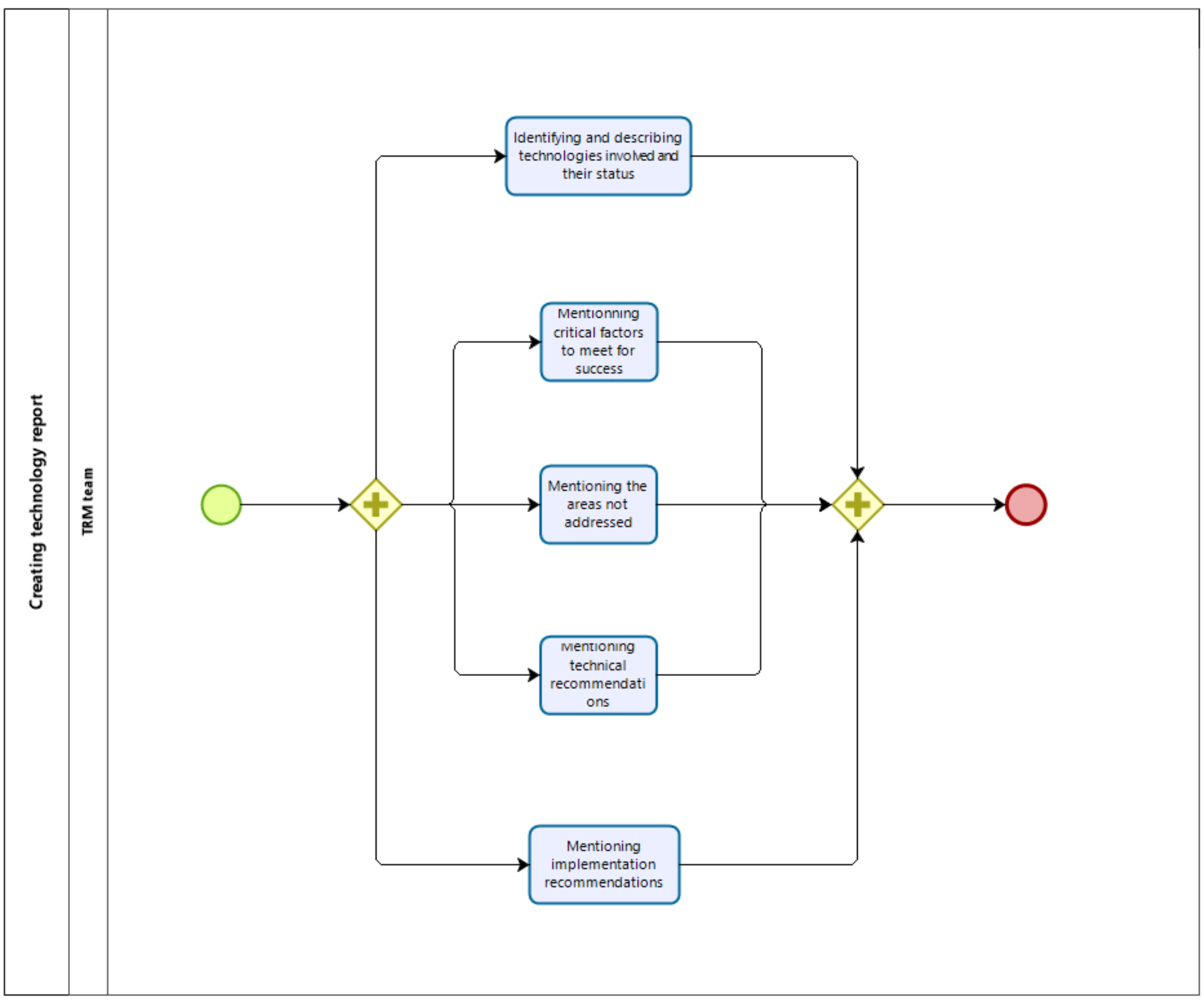


Figure A. 7 TRM phase II, creating the technology report BPMN model.

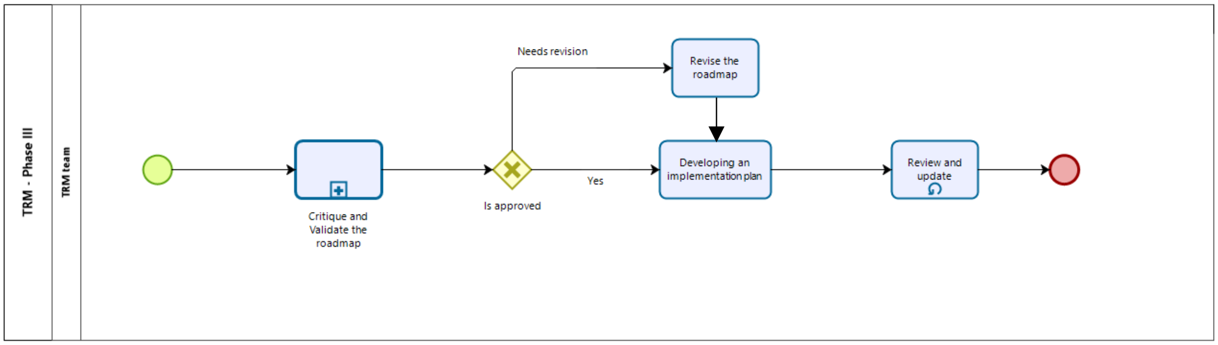


Figure A. 8 TRM Phase III BPMN model.

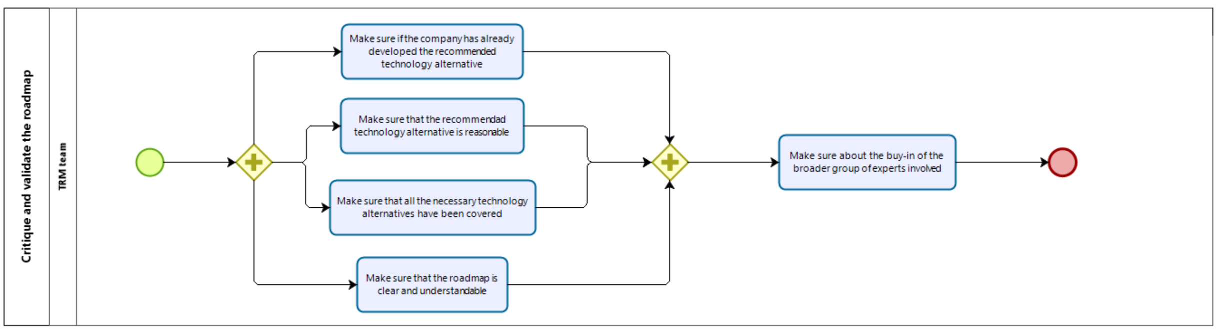


Figure A. 9 TRM phase III, critiquing and validating the roadmap BPMN model.

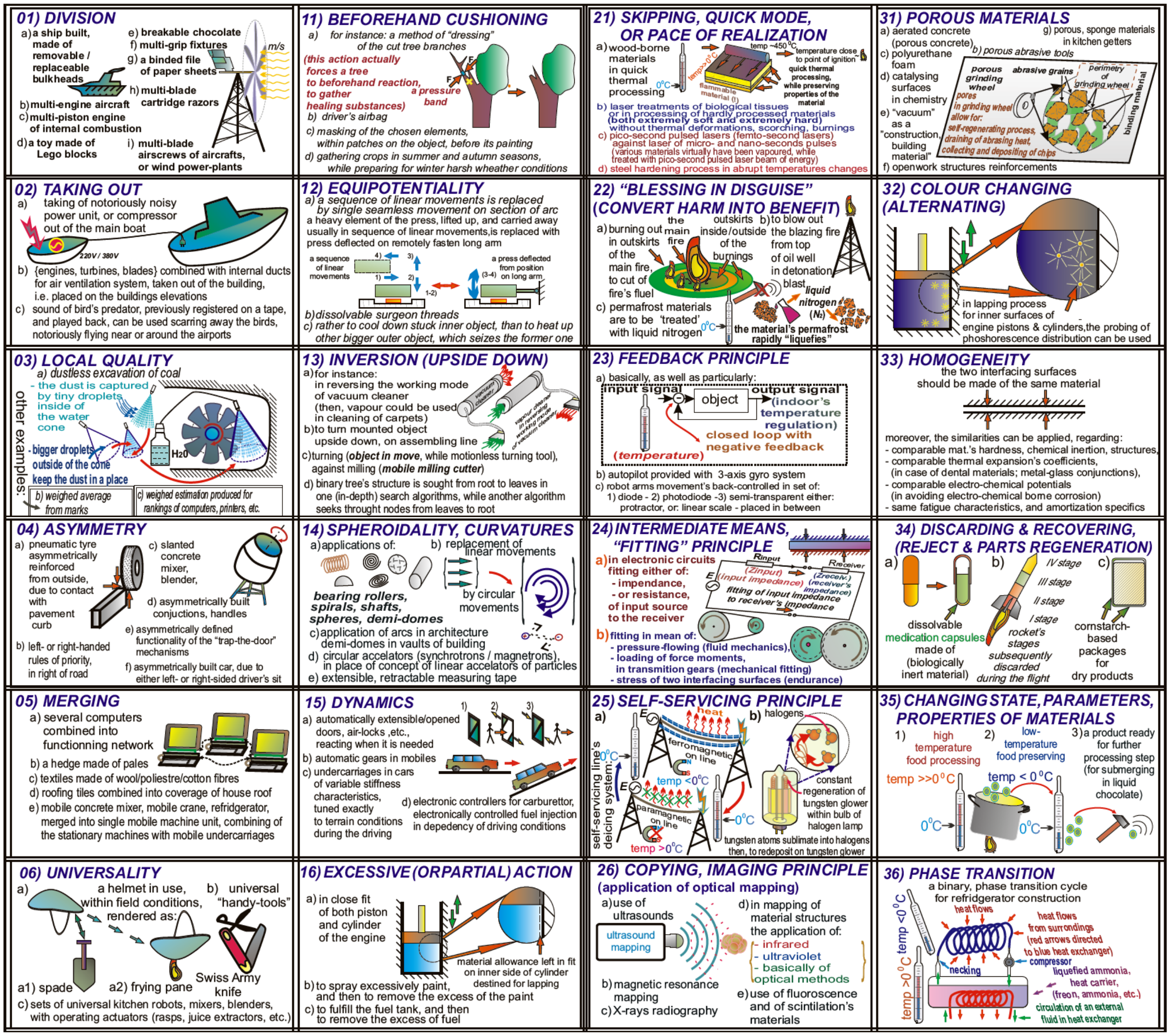
Appendix B

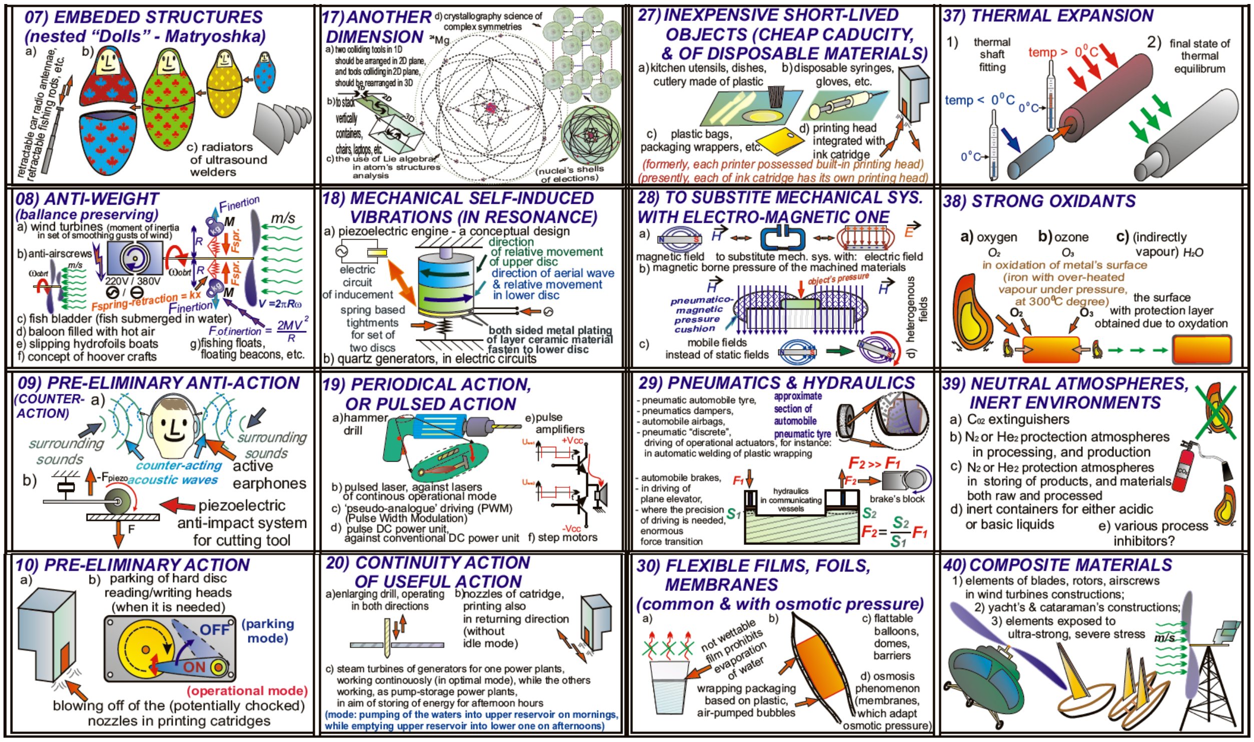
TRIZ Tables, Figures and Additional Concepts

Table B. 1 TRIZ 40 inventive principles

Principle no.	Principle title	Principle no.	Principle title
1	Segmentation (Fragmentation)	**21**	Rushing through (Skipping)
2	Extraction (Taking out)	**22**	Convert harm into a benefit (Blessing in Disguise)
3	Local quality	**23**	Feedback
4	Asymmetry (Symmetry change)	**24**	Mediator (Intermediary)
5	Consolidation (Combining)	**25**	Self-service
6	Universality (Multi Functionality)	**26**	Copying
7	Nesting (Matrioshka)	**27**	Dispose
8	Counterweight (Anti-Weight)	**28**	Replacement of a mechanical system
9	Prior Counteraction	**29**	Pneumatic or Hydraulic construction
10	Prior Action (Do It In Advance)	**30**	Flexile films or thin membranes
11	Cushion in advance (Cushioning)	**31**	Porous materials
12	Equipotentiality	**32**	Changing the color (Color Changes)
13	Do it in reverse (The Other Way Around)	**33**	Homogeneity (Uniformity)
14	Spheroidality (Curvature)	**34**	Rejecting and regenerating parts
15	Dynamicity (Dynamics)	**35**	Transformation of properties
16	Partial or Excessive action	**36**	Phase Transition
17	Transition into a new dimension	**37**	Thermal Expansion (Relative Changes)
18	Vibration	**38**	Accelerated oxidation (Strong Oxidation)
19	Periodic action	**39**	Inert environment (Inert Atmosphere)
20	Continuity of useful actions	**40**	Composite materials

Figure B. 1 TRIZ 40 inventive principles in sketches, rendered into form of vector graphics




07) EMBEDED STRUCTURES
(nested "Dolls" - Matryoshka)
a)
b)
retractable car radio antennae, retractable fishing rods, etc.
c) radiators of ultrasound welders
17) ANOTHER DIMENSION
d) crystallography science of complex symmetries
a) two colliding tools in 1D should be arranged in 2D plane, and tools colliding in 2D plane, should be rearranged in 3D
b) to stack vertically containers, chairs, laptops, etc.
c) the use of Lie algebra in atom's structures analysis
(nuclei's shells of elections)
27) INEXPENSIVE SHORT-LIVED OBJECTS (CHEAP CADUCITY, & OF DISPOSABLE MATERIALS)
a) kitchen utensils, dishes, cutlery made of plastic
b) disposable syringes, gloves, etc.
c) plastic bags, packaging wrappers, etc.
d) printing head integrated with ink catridge
(formerly, each printer possessed built-in printing head)
(presently, each of ink catridge has its own printing head)
37) THERMAL EXPANSION
1) thermal shaft fitting
temp > 0°C
2) final state of thermal equilibrum
temp < 0°C
0°C
08) ANTI-WEIGHT
(ballance preserving)
a) wind turbines (moment of inertia in set of smoothing gusts of wind)
b) anti-airscrews
220V / 380V
Fspring-retraction = kx
Finertion
m/s
V = 2πRω
c) fish bladder (fish submerged in water)
d) baloon filled with hot air
e) slipping hydrofoils boats
f) concept of hoover crafts
g) fishing floats, floating beacons, etc.
18) MECHANICAL SELF-INDUCED VIBRATIONS (IN RESONANCE)
a) piezoelectric engine - a conceptual design
electric circuit of inducement
direction of relative movement of upper disc
direction of aerial wave & relative movement in lower disc
spring based tightments for set of two discs
both sided metal plating of layer ceramic material fasten to lower disc
b) quartz generators, in electric circuits
28) TO SUBSTITE MECHANICAL SYS. WITH ELECTRO-MAGNETIC ONE
a)
magnetic field to substitute mech. sys. with: electric field
b) magnetic borne pressure of the machined materials
object's pressure
pneumatico-magnetic pressure cushion
c) mobile fields instead of static fields
d) heterogenous fields
38) STRONG OXIDANTS
a) oxygen O_2
b) ozone O_3
c) (indirectly vapour) H_2O
in oxidation of metal's surface (iron with over-heated vapour under pressure, at 300°C degree)
the surface with protection layer obtained due to oxydation
09) PRE-ELIMINARY ANTI-ACTION (COUNTER-ACTION)
a)
surrounding sounds
counter-acting acoustic waves
active earphones
b)
-Fpiezo
F
piezoelectric anti-impact system for cutting tool
19) PERIODICAL ACTION, OR PULSED ACTION
a) hammer drill
b) pulsed laser, against lasers of continous operational mode
c) 'pseudo-analogue' driving (PWM) (Pulse Width Modulation)
d) pulse DC power unit, against conventional DC power unit
e) pulse amplifiers
+Vcc
-Vcc
f) step motors
29) PNEUMATICS & HYDRAULICS
- pneumatic automobile tyre,
- pneumatics dampers,
- automobile airbags,
- pneumatic "discrete", driving of operational actuators, for instance: in automatic welding of plastic wrapping
approximate section of automobile pneumatic tyre
- automobile brakes,
- in driving of plane elevator,
- where the precision of driving is needed, enormous force transition
hydraulics in communicating vessels
brake's block
$F_2 >> F_1$
$F_2 = \frac{S_2}{S_1} F_1$
39) NEUTRAL ATMOSPHERES, INERT ENVIRONMENTS
a) CO_2 extinguishers
b) N_2 or He_2 proctection atmospheres in processing, and production
c) N_2 or He_2 protection atmospheres in storing of products, and materials both raw and processed
d) inert containers for either acidic or basic liquids
e) various process inhibitors?
10) PRE-ELIMINARY ACTION
a)
b) parking of hard disc reading/writing heads (when it is needed)
OFF (parking mode)
ON (operational mode)
blowing off of the (potentially chocked) nozzles in printing catridges
20) CONTINUITY ACTION OF USEFUL ACTION
a) enlarging drill, operating in both directions
b) nozzles of catridge, printing also in returning direction (without idle mode)
c) steam turbines of generators for one power plants, working continouosly (in optimal mode), while the others working, as pump-storage power plants, in aim of storing of energy for afternoon hours
(mode: pumping of the waters into upper reservoir on mornings, while emptying upper reservoir into lower one on afternoons)
30) FLEXIBLE FILMS, FOILS, MEMBRANES
(common & with osmotic pressure)
a)
not wettable film prohibits evaporation of water
wrapping packaging based on plastic, air-pumped bubbles
b)
c) flattable balloons, domes, barriers
d) osmosis phenomenon (membranes, which adapt osmotic pressure)
40) COMPOSITE MATERIALS
1) elements of blades, rotors, airscrews in wind turbines constructions;
2) yacht's & cataraman's constructions;
3) elements exposed to ultra-strong, severe stress
m/s

Additional TRIZ tools:

- **Bad Solutions Park**

  Throughout the problem-solving process, many solutions will be suggested that are either not reasonable or not feasible, usually because the problem is not fully understood at that stage. A bad solution park is a temporary store (or park) for these solutions. Although the ideas on bad solutions park are not suitable, they can serve as valuable starting points in the following stages of the process, once the problem is understood properly. Therefore, bad solutions park records them and keeps them in temporary storage for the future.

- **Asking Why and How?**

  It is critical to properly understand why we are trying to develop a solution and how this solution works in every stage of problem-solving. This way, the problem-solvers will always be focused on the required benefits by the system and which functions will deliver those benefits. Moreover, this will make the team keep an eye on the required resources for potential solutions. Figure 2.29 illustrates how the entire hierarchy of problem-solving from required resources (the lowest level) to the ideal outcome (the highest level) can be linked through these two critical questions. These questions also help the problem-solvers to avoid premature solutions.

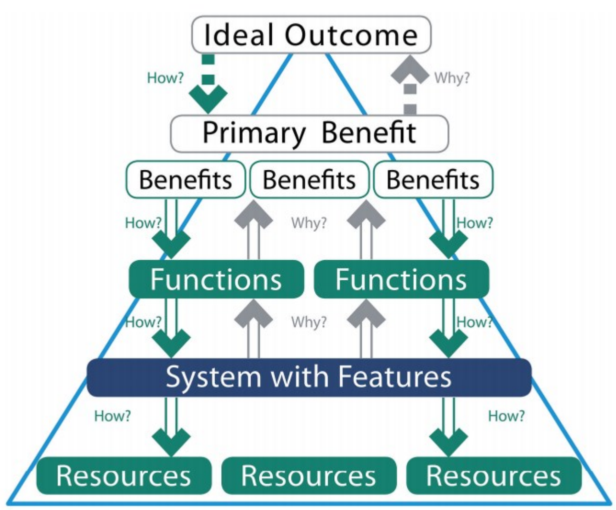
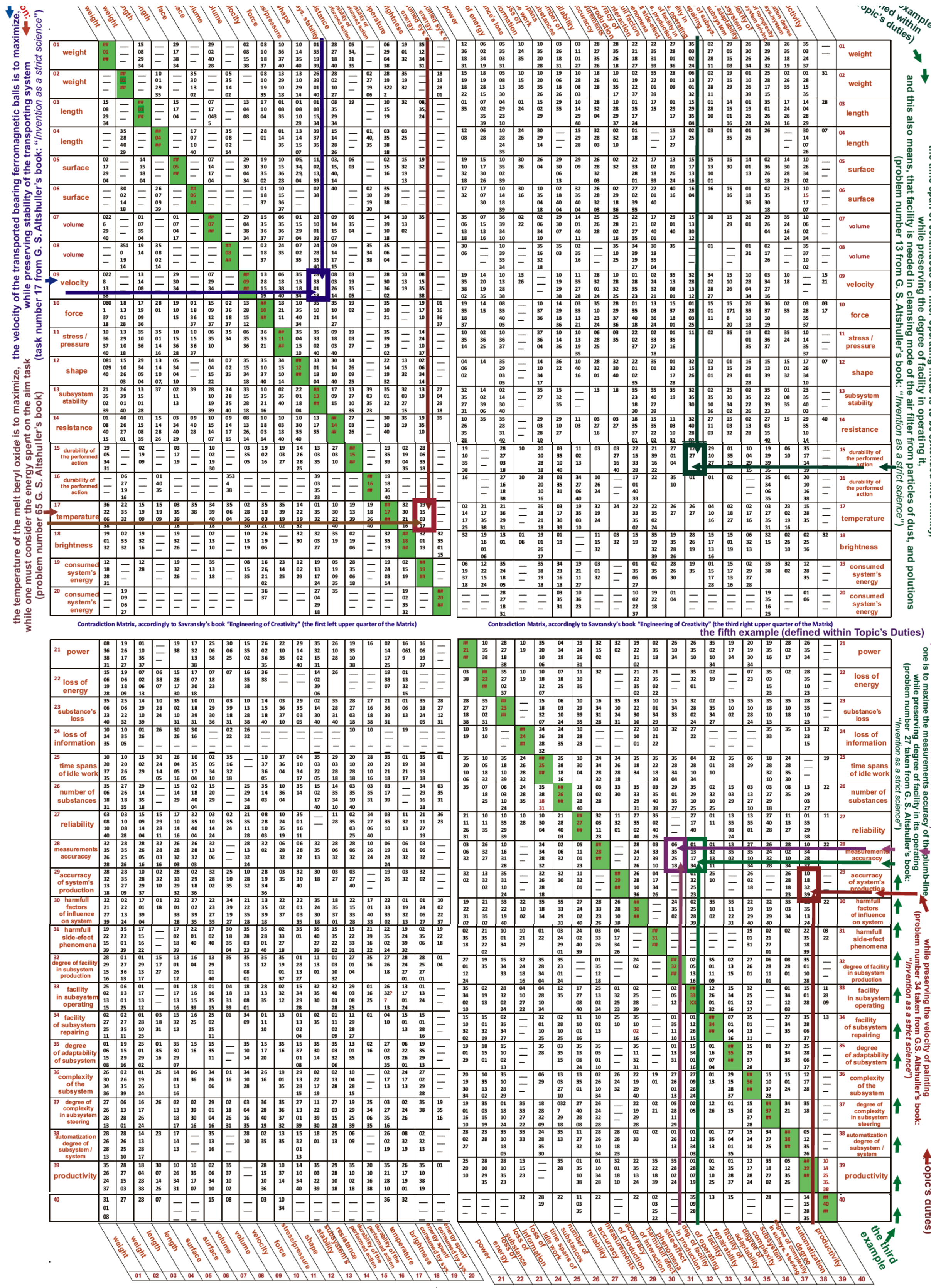


Figure B. 2 Asking How and Why in problem-solving. Adopted from Gadd (2011).

Figure B. 3 TRIZ contradiction matrix



Appendix C

TRIZ 76 Standard Solutions

Class 1: Improving the system with no or little change

1.1. Improving the performance of an inadequate system

1.1.1. Complete an incomplete model. If there is only an object S1, add a second object S2 and an interaction (field).

1.1.2. The system cannot be changed, but a permanent or temporary additive is acceptable. Incorporate an internal additive in either S1 or S2.

1.1.3. As in 1.1.2, but use a pe1manent or tempora1y external additive S3 to change either SI or S2.

1.1.4. As in 1.1.2, but use a resource from the environment as the additive, either internally or externally.

1.1.5. As in 1.1.2, but modify or change the environment of the system.

1.1.6. Precise control of small amounts is challenging to achieve—Control small quantities by applying and removing a surplus.

1.1.7. If a will moderate damage field the can system, be the applied larger which is magnitude insufficient field can for be the applied desired to effect, another and an element greater field will damage the system, the larger magnitude field can be applied to another element which can be linked to the original. Likewise, a substance that cannot take the full action directly but can achieve the desired effect through linkage to another substance can be used.

1.1.8. A pattern of large/strong and small/weak effects is required. The locations requiring the smaller effects can be protected by a substance S3.

1.2. Eliminating or neutralizing harmful effects.

1.2.1. Useful and harmful effects exist in the current design. It is not necessary for S1 and S2 to be in direct contact. Remove the harmful effect by introducing S3.

1.2.2. Similar to 1.2.1., but new substances cannot be added. Remove the harmful effect by modifying S1 or S2. This solution includes adding "nothing"-voids, hollows, vacuum, air, bubbles, foam, etc., or adding a field that acts as an additional substance.

1.2.3. The harmful action is caused by a field. Introduce an element S3 to absorb the harmful effects.

1.2.4. Useful and harmful effects exist in a system in which the elements S1 and S2 must be in contact. Counteract the harmful effect of F1 by having F2 neutralize the harmful effect or gain an additional useful effect.

1.2.5. A harmful effect may exist because of the magnetic properties of an element in a system. The effect can be removed by heating the magnetic substance above its Curie point or by introducing an opposite magnetic field.

Class 2: Improving the system by changing the system

2.1. Improving the performance of an inadequate system

2.1.1. Chain Su-Field Model: Convert the single model to a chained model by having S2 with F1 applied to S3, which in turn applies F2 to S1. The sequence of two models can be independently controlled.

2.1.2. 2.1.2. Double Su-Field Model: A poorly controlled system needs to be improved, but you may not change the elements of the existing system. A second field can be applied to S2.

2.2. Forcing the Su-Field Models

2.2.1. 2.2.1. Replace or add to the poorly controlled field with a more easily controlled field. Going from a gravitational field to a mechanical field provides more control, as does going from mechanical means to electrical or mechanical to magnetic. This is one of the patterns of evolution of systems progressing from objects in physical contact to actions done by fields.

2.2.2. Change S2 from a macro level to a micro-level, i.e., instead of a rock, consider particles. This standard is actually the pattern of evolution from a macro- to micro-level.

2.2.3. Change S2 to a porous or capillary material that will allow gas or liquid to pass through.

2.2.4. Make the system more flexible or adaptable; becoming more dynamic is another pattern of evolution. The common transition is from a solid to a hinged system to continuous flexible systems.

2.2.5. Change an uncontrolled field to a field with predetermined patterns that may be permanent or temporary.

2.2.6. Change a uniform substance or uncontrolled substance to a non-uniform substance with a predetermined spatial structure that may be permanent or temporary.

2.3. Controlling the frequency to match or mismatch the natural frequency of one or both elements to improve performance.

2.3.1. Matching or mismatching the frequency of F and S1 or S2.

2.3.2. Matching the rhythms of F1 and F2.

2.3.3. Two incompatible or independent actions can be accomplished by running each during the downtime of the other.

2.4. Integrating ferromagnetic material and magnetic fields is an effective way to improve the performance of a system. In Su-field models, the magnetic field due to a ferromagnetic material is given the special designation Fe-field, or F_{Fe}.

2.4.1. Add ferromagnetic material and/or a magnetic field to the system.

2.4.2. Combine 2.2.1 (going to more controlled fields) and 2.4.1 (using ferromagnetic materials and magnetic fields).

2.4.3. Use a magnetic liquid. Magnetic liquids are a special case of 2.4.2. Magnetic liquids are colloidal ferromagnetic particles suspended in kerosene, silicone, or water.

2.4.4. Use capillary structures that contain magnetic particles or liquid.

2.4.5. Use additives (such as a coating) to give a non-magnetic object magnetic properties. It may be temporary or permanent.

2.4.6. Introduce ferromagnetic materials into the environment if it is not possible to make the object magnetic.

2.4.7. Use natural phenomena (such as alignment of objects with the field or loss of ferromagnetism above the Curie point.)

2.4.8. Use a dynamic, variable, or self-adjusting magnetic field.

2.4.9. Modify the structure of a material by introducing ferromagnetic particles, then apply a magnetic field to move the particles. More generally, the transition from an unstructured system to a structured one, or vice versa, depending on the situation.

2.4.10. Matching the rhythms in the Fe-field models. In macro-systems, this is the use of mechanical vibration to enhance the motion of ferromagnetic particles. At the molecular and atomic levels, the material composition can be identified by the spectrum of the resonance frequency of electrons in response to changing frequencies of a magnetic field.

2.4.11. Use electric current to create magnetic fields instead of using magnetic particles.

2.4.12. Rheological liquids have viscosity controlled by an electric field. They can be used in combination with any of the methods here. They can mimic liquid/solid phase transitions.

Class 3: System transitions to super-system or micro-level

3.1. Transition to the Bi- and Poly-System

3.1.1. System Transition 1a: Creating the Bi- and Poly-Systems.

3.1.2. Improving Links in the Bi- and Poly-Systems.

3.1.3. System Transition 1b: Increasing the Differences Between Elements.

3.1.4. Simplification of the Bi- and Poly-Systems.

3.1.5. System Transition 1c: Opposite Features of the Whole and Parts.

3.2. Transition to the Micro-Level

3.2.1. System Transition 2: Transition to the Micro-Level.

Class 4: Detection and measurement

4.1. Indirect Methods

4.1.1. Modify the system instead of detecting or measuring, so there is no longer a need for measurement.

4.1.2. Measure a copy or an image if 4.1.1 can't be used.

4.1.3. Use 2 detections instead of continuous measurement if 4.1.1 or 4.1.2 cannot be used. For example, make a ring with a machined part's outer tolerance limits and a solid having its diameter equal to the inner tolerance limit. The part is the right diameter when it fits through the ring (one detection), and the solid fits through it (second detection.)

4.2. Create or synthesize a measurement system. Some elements or fields must be added to the existing system

4.2.1. If an incomplete Su-field system cannot be detected or measured, a single or double Su-field system with a field as an output is created. If the existing field is inadequate, change or enhance the field without interfering with the original system. The new or enhanced field should have an easily detectable parameter that correlates to the parameter we need to know.

4.2.2. Measure an introduced additive. Introduce an additive that reacts to a change in the original system, then measure the changes in the additive.

4.2.3. If nothing can be added to the system, then detect or measure the system's effect on a field created by additive(s) placed in the external environment.

4.2.4. If additives cannot be introduced into the system's environment as in 4.2.3, then create them by decomposing or changing the state of something that is already in the environment and measure the system's effectiveness on these created additives.

4.3. Enhancing the measurement system

4.3.1. Apply natural phenomena. Use scientific effects that are known to occur in the system, and determine the state of the system by observing changes in the effects.

4.3.2. If changes in a system cannot be determined directly or by passing a field, measure the excited resonant frequency of the system or an element in order to measure changes.

4.3.3. If 4.3.2 is not possible, measure the resonant frequency of the object joined to another of known properties.

4.4. Measure Fe-field: The introduction of ferromagnetic materials for measurement was popular before the development of remote sensing, miniature devices, fiber optics, microprocessors, etc.

4.4.1. Add or make use of a ferromagnetic substance and a magnetic field in a system (by means of permanent magnets or loops of electric current) to facilitate measurement.

4.4.2. Add magnetic particles to a system or change a substance to ferromagnetic particles to facilitate measurement by detecting the resulting magnetic field.

4.4.3. If ferromagnetic particles cannot be added directly to the system or a substance cannot be replaced with ferromagnetic particles, construct a complex system by putting ferromagnetic additives into the substance.

4.4.4. Add ferromagnetic particles to the environment if they cannot be added to the system.

4.4.5. Measure the effects of natural phenomena associated with magnetism such as the Curie point, hysteresis, quenching of superconductivity, the Hall effect, etc.

4.5. Direction of Evolution of the Measuring Systems

4.5.1. Transition to bi- and poly-systems. If a single measurement system does not give sufficient accuracy, use two or more measuring systems, or make multiple measurements.

4.5.2. Instead of directly measuring a phenomenon, measure the first and second derivatives in time or in space. For example, measure velocity and acceleration instead of measuring position. Measure the rate of frequency change of a sound (Doppler shift) to determine the velocity of the source.

Class 5: Strategies for simplification and improvement

5.1. Introducing Substances

5.1.1. Indirect ways

5.1.1.1. Use "nothing" –add air, vacuum, .bubbles, foam, voids, hollows, clearances, capillaries, pores, holes, voids, etc.

5.1.1.2. Use a field instead of a substance.

5.1.1.3. Use an external additive instead of an internal one.

5.1.1.4. Use a small amount of a very active additive.

5.1.1.5. Concentrate the additive at a specific location.

5.1.1.6. Introduce the additive temporarily.

5.1.1.7. Use a copy or model of the object in which additives can be used instead of the original object if additives are not permitted in the original. In modern use, this would include the use of simulations and copies of the additives.

5.1.1.8. Introduce a chemical compound that reacts, yielding the desired elements or compounds, where introducing the desired material would be harmful.

5.1.1.9. Obtain the required additive by decomposition of either the environment or the object itself.

5.1.2. Divide the elements into smaller units.

5.1.3. The additive eliminates itself after use.

5.1.4. Use "nothing" if circumstances do not permit the use of large quantities of material.

5.2. Use fields

5.2.1. Use one field to cause the creation of another field

5.2.2. Use fields that are present in the environment.

5.2.3. Use substances that are the sources of fields.

5.3. Phase Transitions

5.3.1. Phase Transition 1: Substituting the Phases.

5.3.2. Phase Transition 2: Dual-Phase State.

5.3.3. Phase Transition 3: Utilizing the Accompanying Phenomena of the Phase Change.

5.3.4. Phase Transition 4: Transition to the Two-Phase State.

5.3.5. Interaction of the Phases. Increase the system's effectiveness by inducing an interaction between the elements of the system or the phases of the system.

5.4. Applying the Natural Phenomena (Also called "Using Physical Effects")

5.4.1. Self-controlled Transitions. If an object must be in several different states, it should transition from one state to the other by itself.

5.4.2. Strengthening the output field when there is a weak input field. Generally, this is done by working near a phase transition point.

5.5. Generating Higher or Lower Forms of Substances

5.5.1. Obtaining the Substance Particles (Ions, Atoms, Molecules, etc.) by Decomposition.

5.5.2. Obtaining the substance particles by joining.

5.5.3. Applying the Standard Solutions 5.5.1 and 5.5.2. If a substance of a high structural level has to be decomposed and cannot be decomposed, start with the substance of the next highest level. Likewise, if a substance must be formed from materials of a low structural level, and it cannot be, then start with the next higher level of structure.

Appendix D

Conceptual Framework Flowcharts

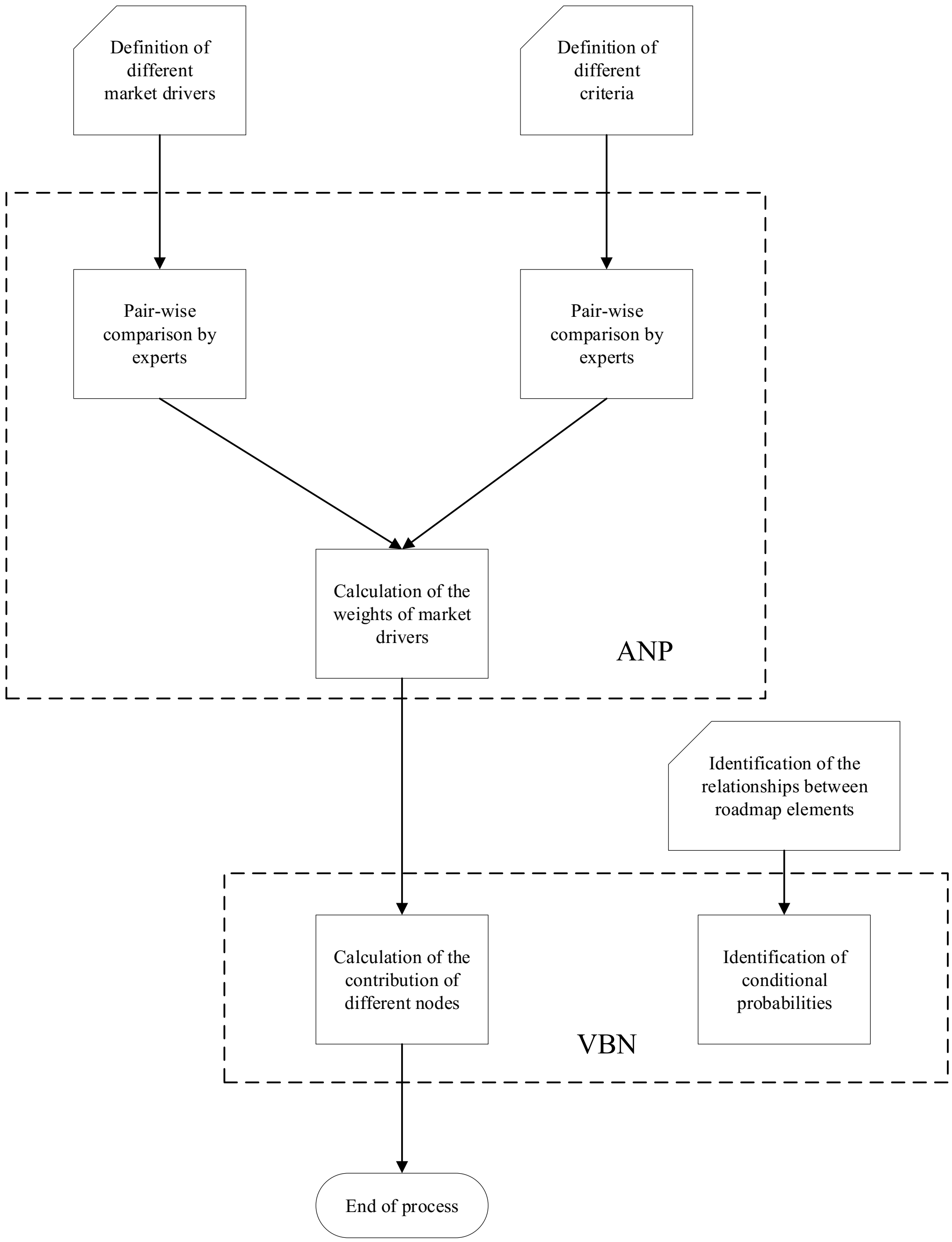
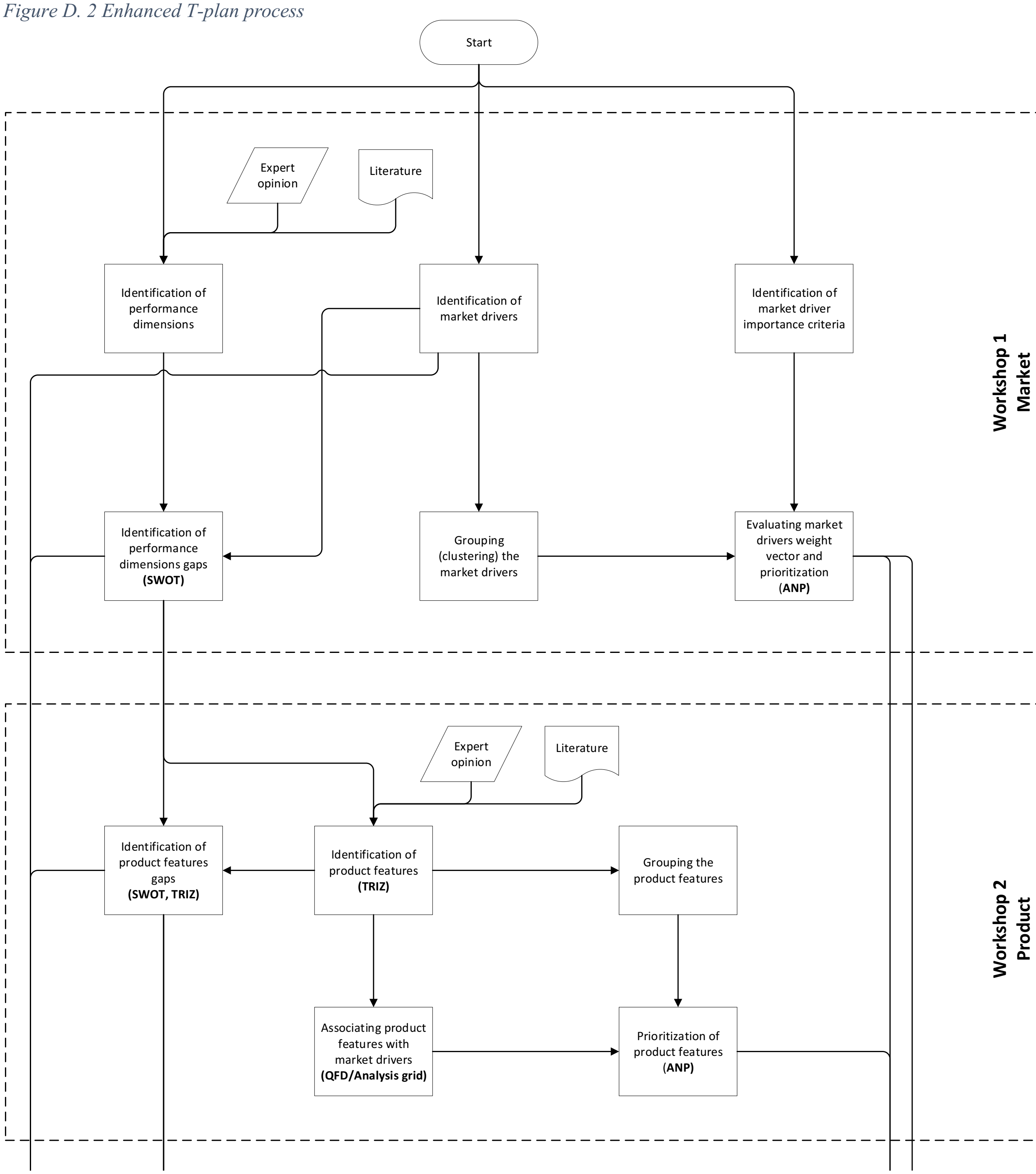
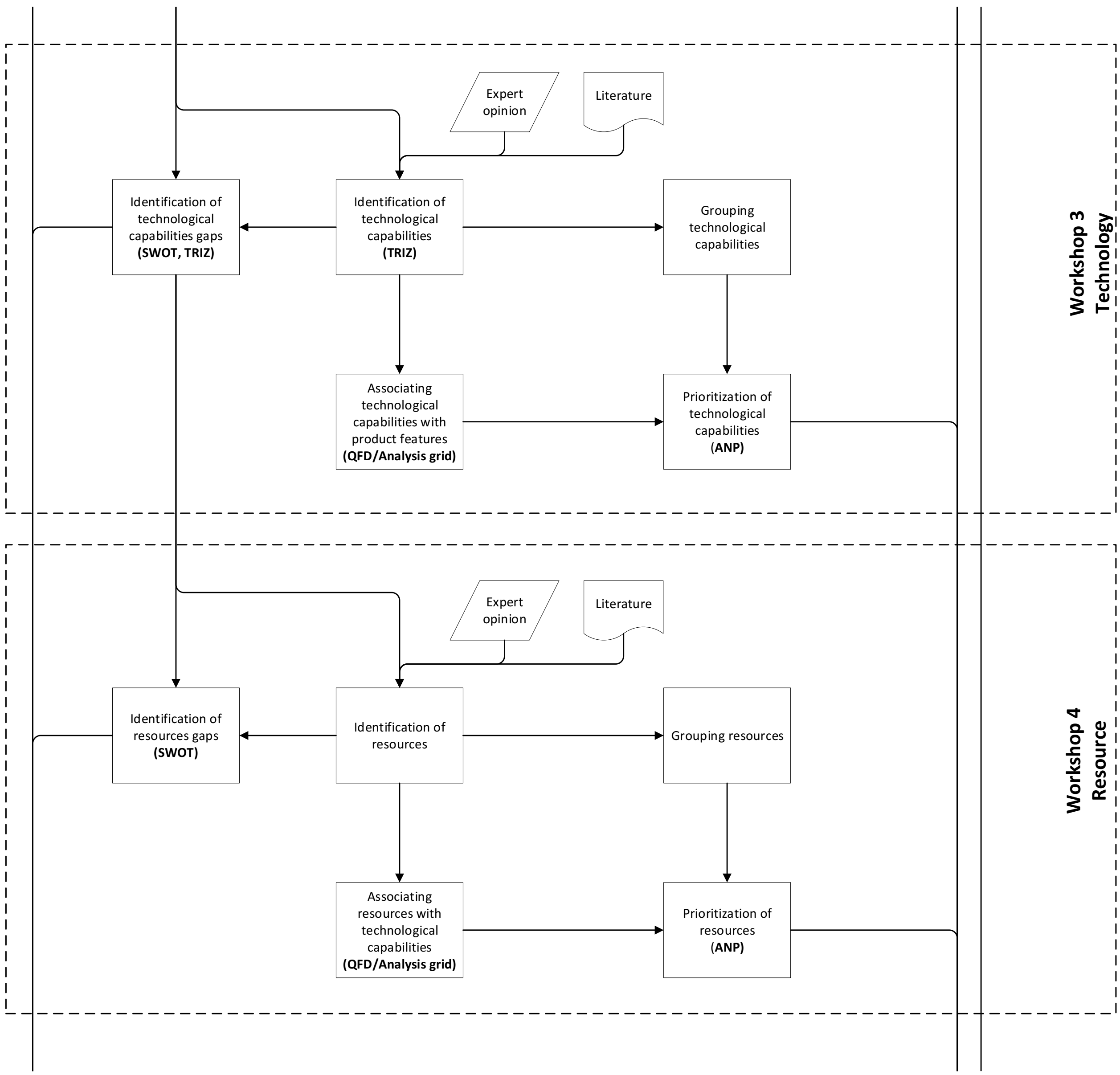


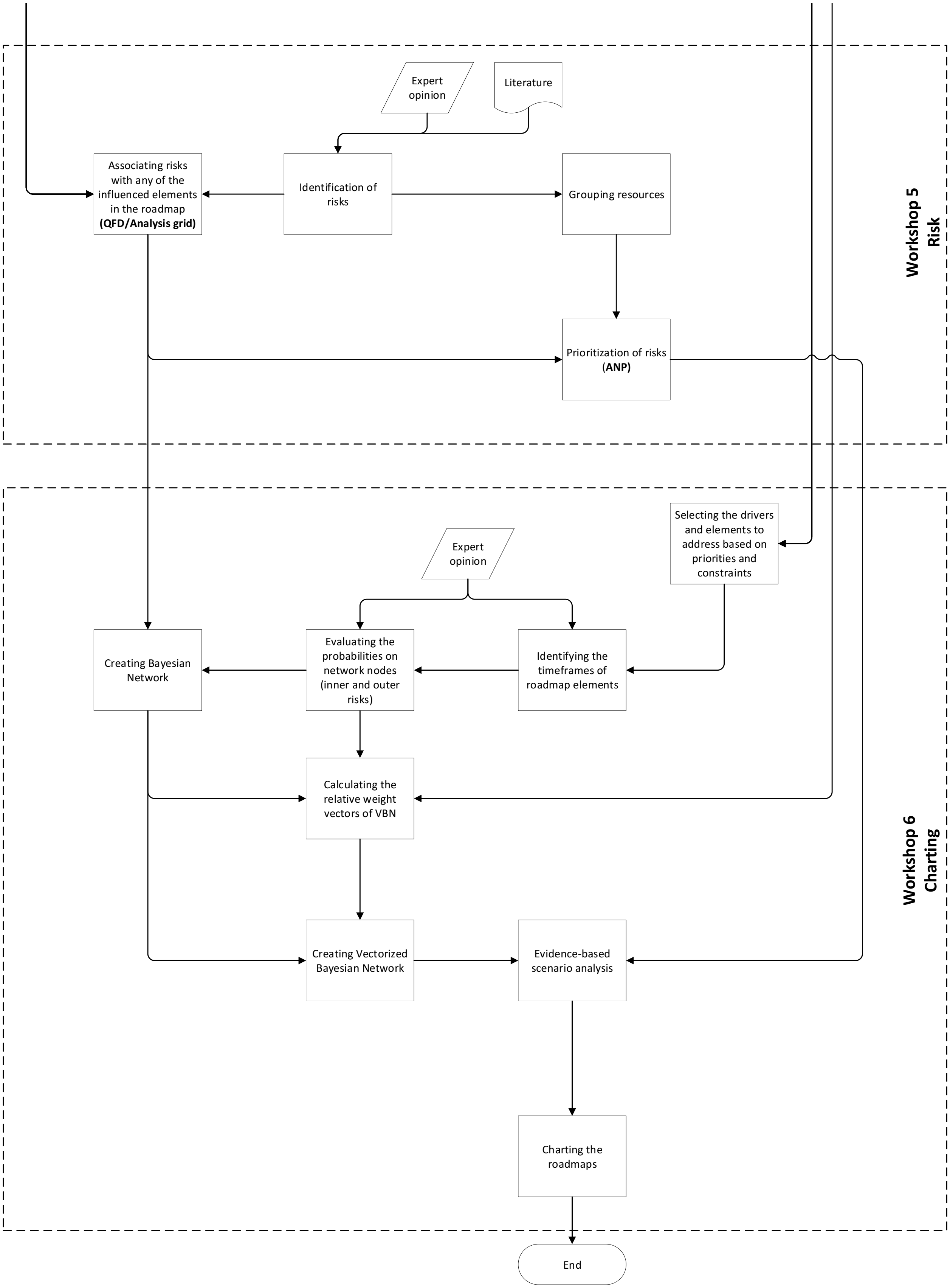
Figure D. 1 Procedure of ANP and VBN integration

Figure D. 2 Enhanced T-plan process





Expert opinion
Literature
Identification of technological capabilities gaps **(SWOT, TRIZ)**
Identification of technological capabilities **(TRIZ)**
Grouping technological capabilities
Associating technological capabilities with product features **(QFD/Analysis grid)**
Prioritization of technological capabilities **(ANP)**
Workshop 3 Technology
Expert opinion
Literature
Identification of resources gaps **(SWOT)**
Identification of resources
Grouping resources
Associating resources with technological capabilities **(QFD/Analysis grid)**
Prioritization of resources **(ANP)**
Workshop 4 Resource


Expert opinion
Literature
Associating risks with any of the influenced elements in the roadmap **(QFD/Analysis grid)**
Identification of risks
Grouping resources
Prioritization of risks **(ANP)**
Workshop 5 Risk
Selecting the drivers and elements to address based on priorities and constraints
Expert opinion
Creating Bayesian Network
Evaluating the probabilities on network nodes (inner and outer risks)
Identifying the timeframes of roadmap elements
Calculating the relative weight vectors of VBN
Creating Vectorized Bayesian Network
Evidence-based scenario analysis
Charting the roadmaps
Workshop 6 Charting
End

Appendix E

Case study Figures

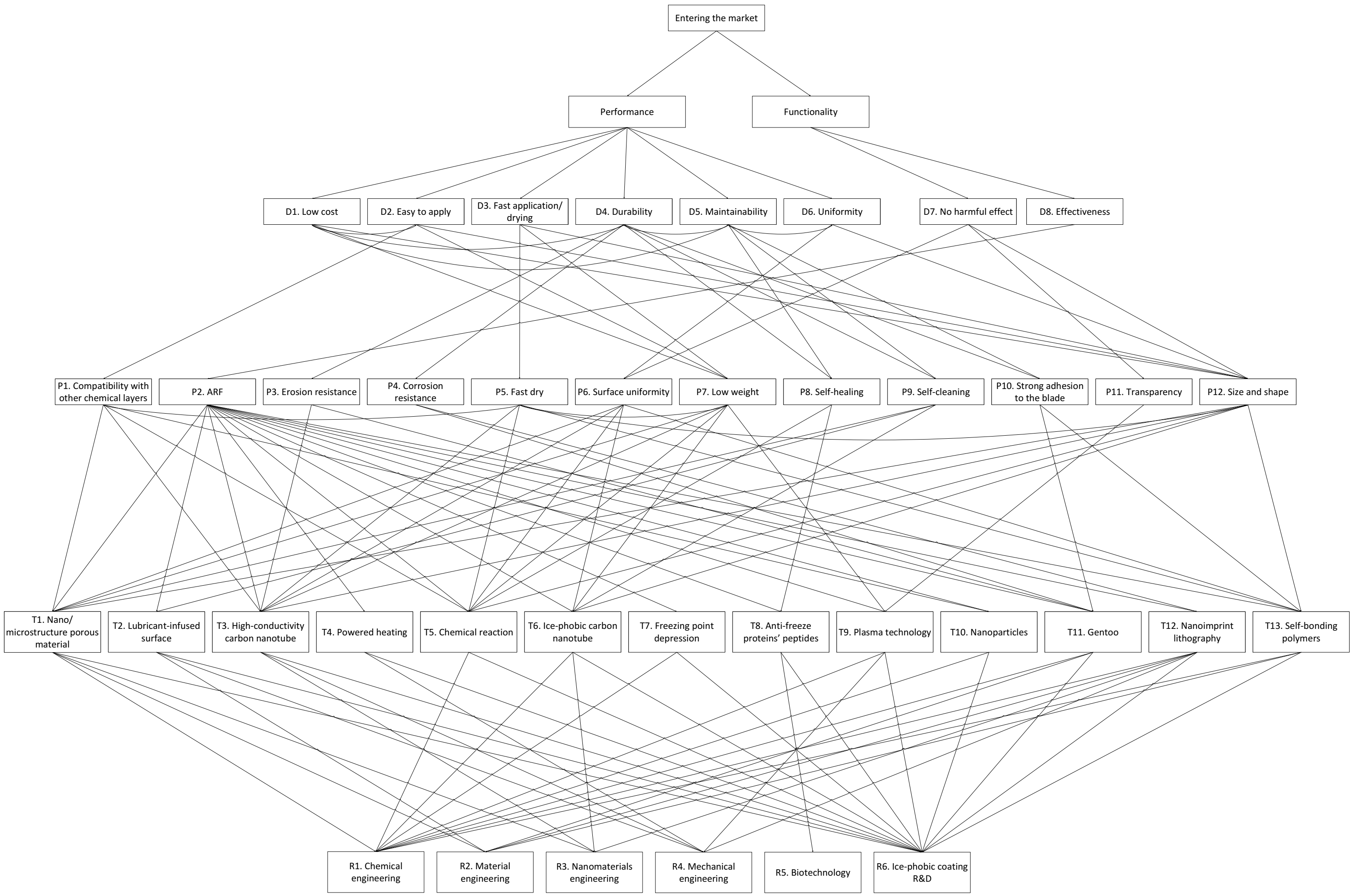


Figure E. 1 Original universal ANP model

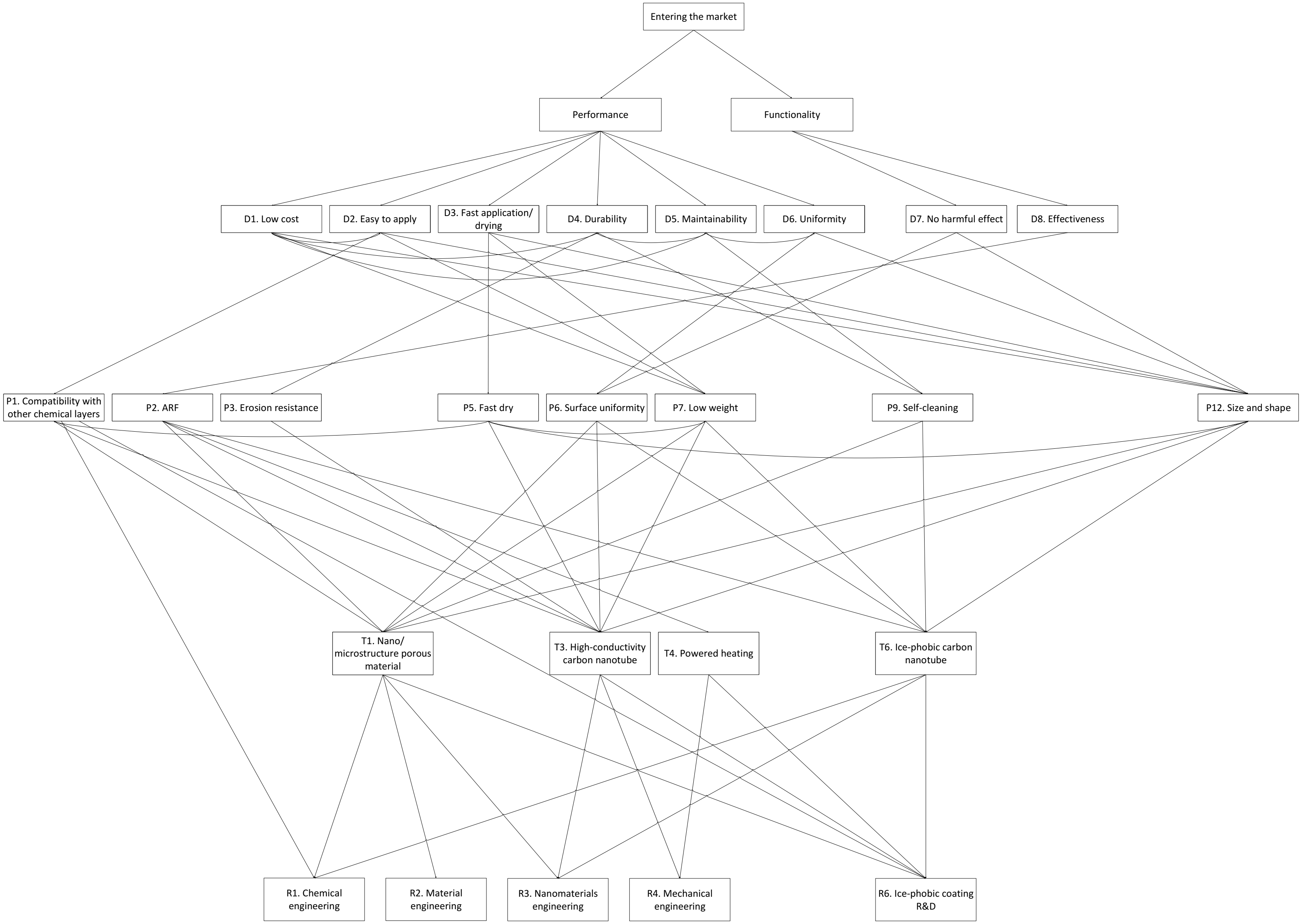


Figure E. 2 Reduced universal ANP model

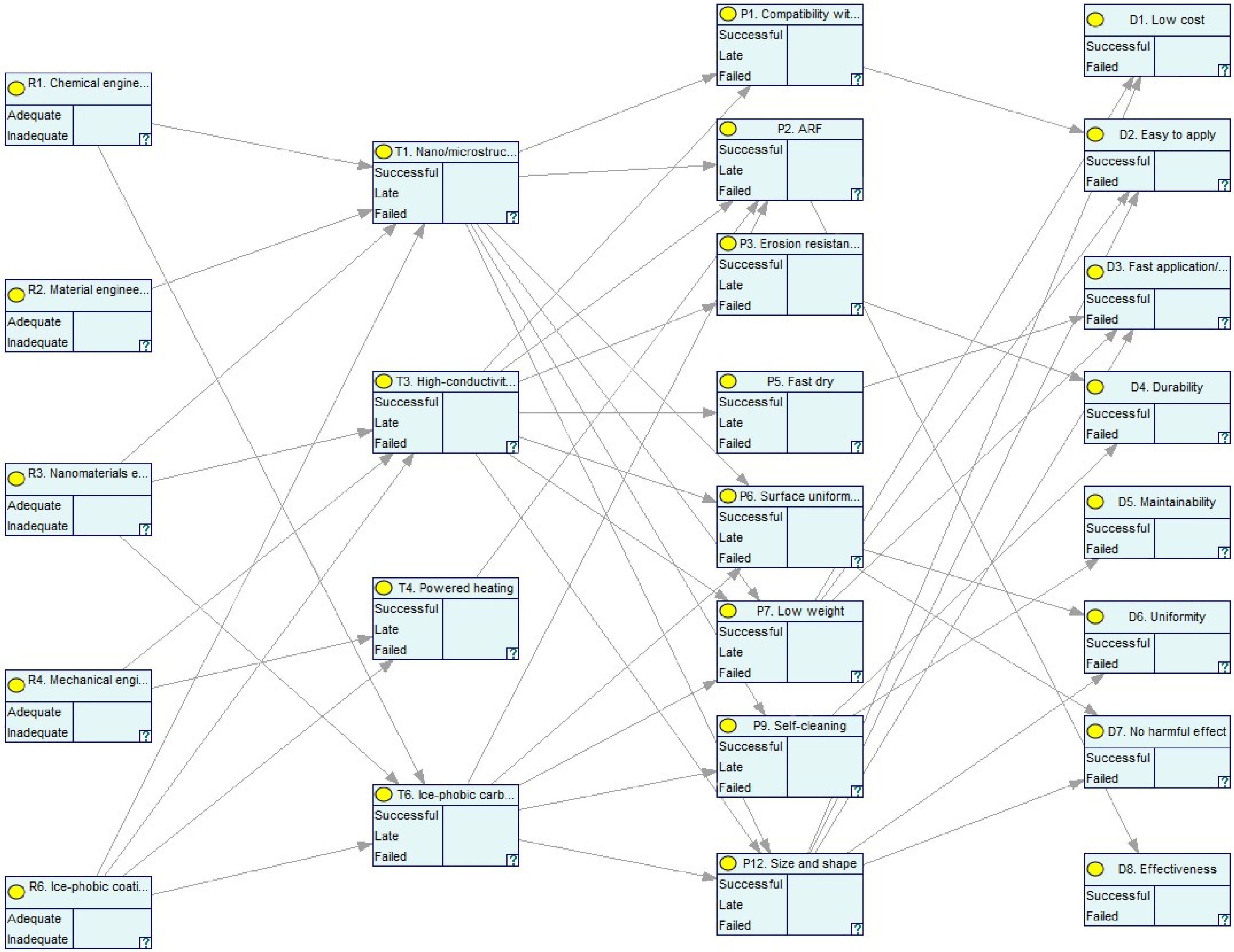


Figure E. 3 The Bayesian Network of the reduced model

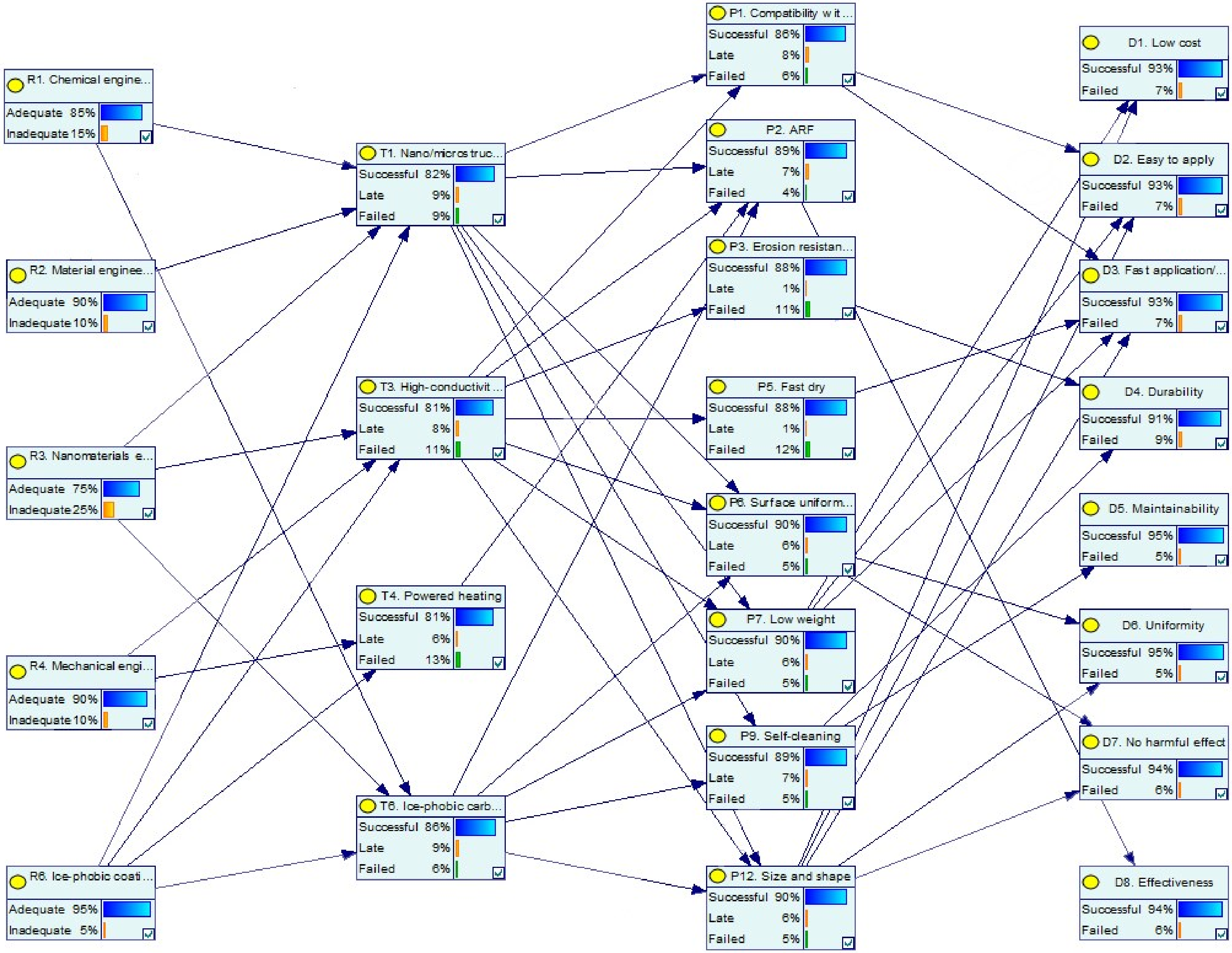


Figure E. 4 Probabilistic Network of intrinsic risks

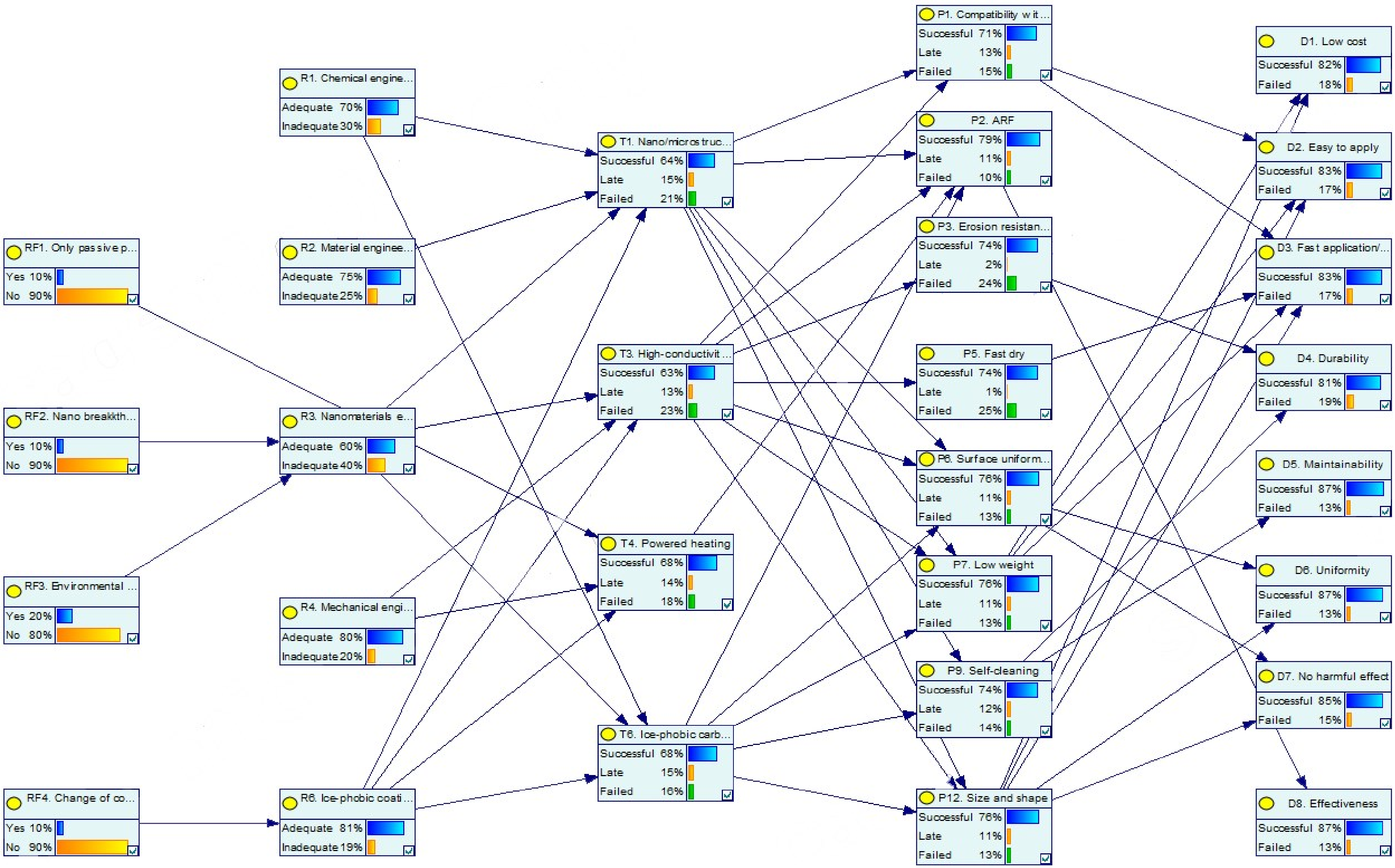


Figure E. 5 Probabilistic network of non-intrinsic and intrinsic risks

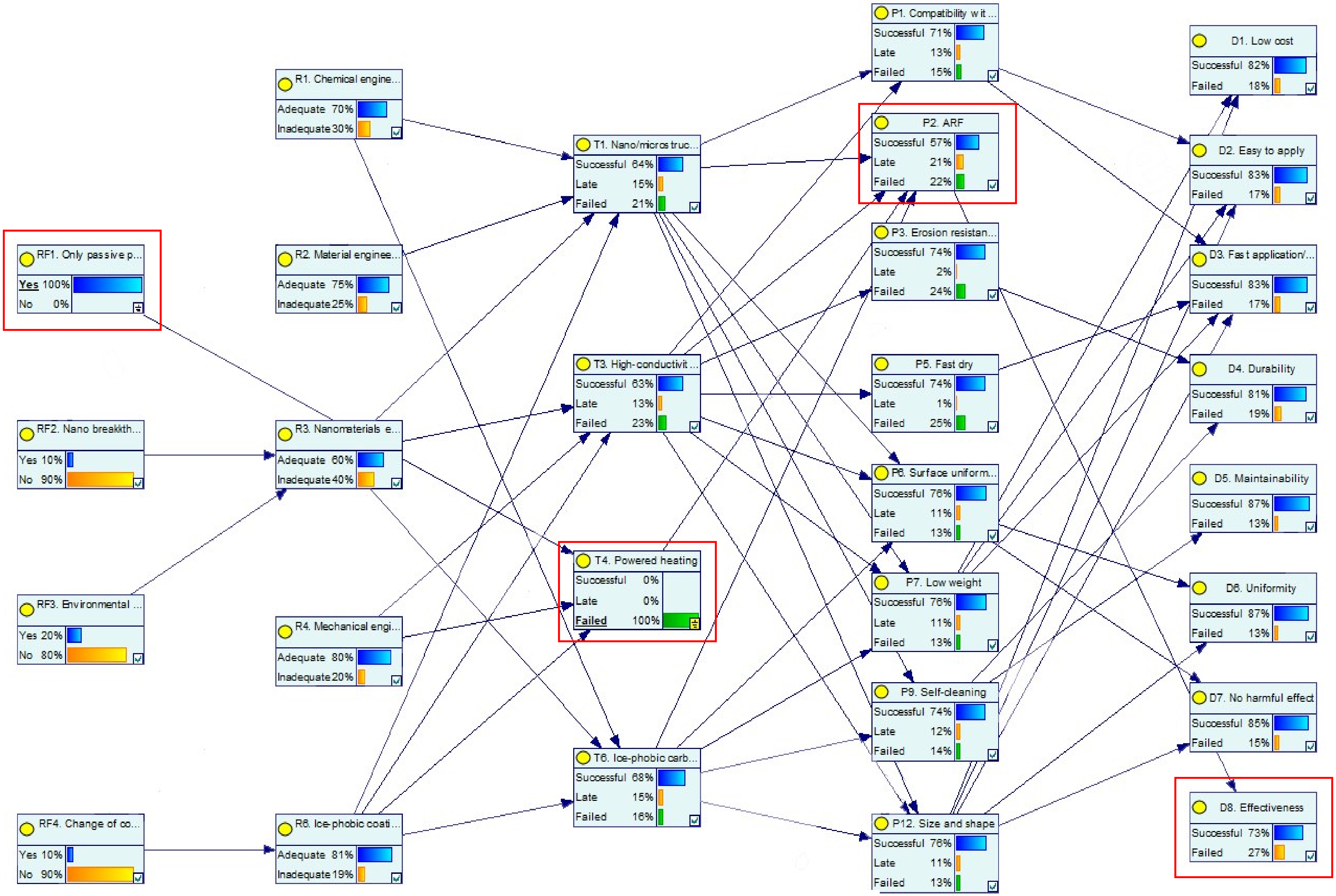


Figure E. 6 Scenario #1: RF1 occurrence

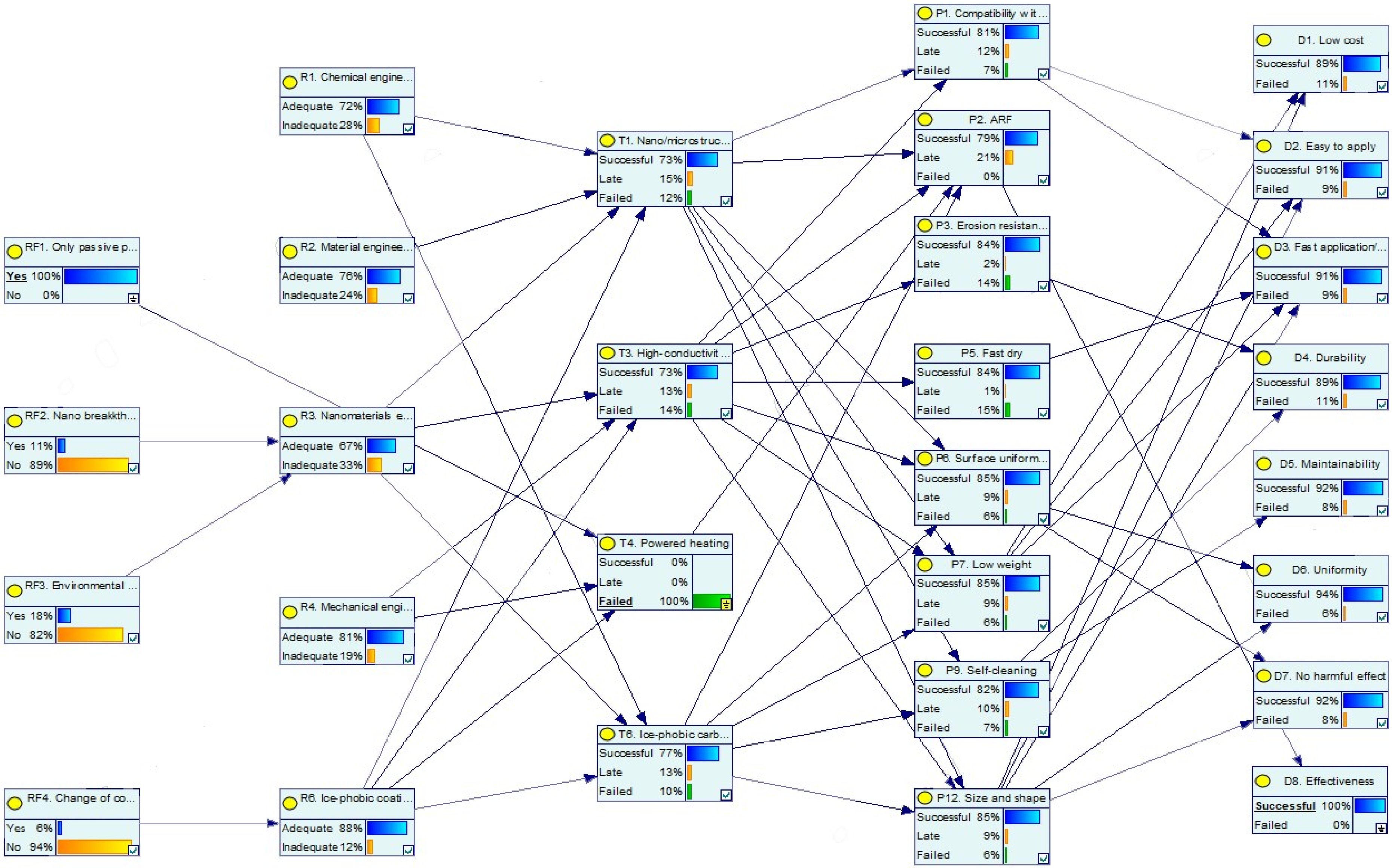


Figure E. 7 Scenario #1: RF1 occurrence while assuring D8

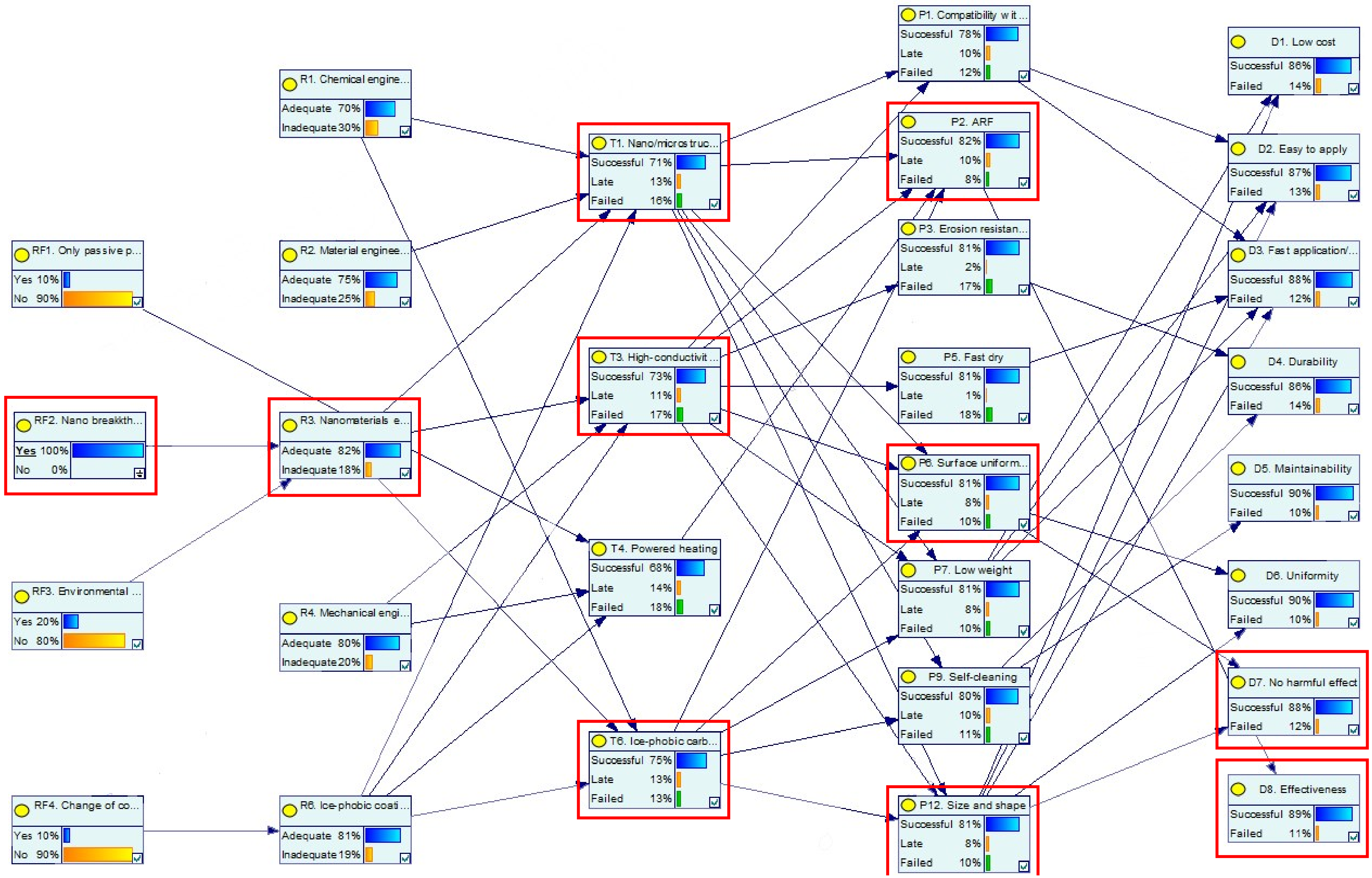


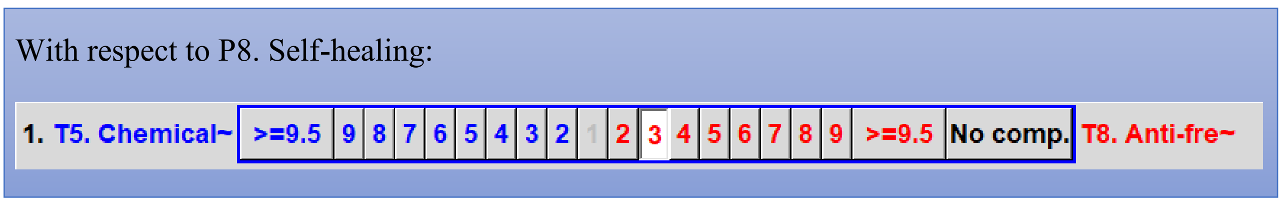
Figure E. 8 Scenario #2: RF2 occurrence

Appendix F

Paired-wise Comparisons

The figures in this appendix are screenshots of the SuperDecisions software questionnaire consisting of the paired-wise comparisons. Each row represents a comparative scale to evaluate the importance or weight of one factor in direct comparison to another with respect to a criterion.

For example, the figure below shows that the technological capability **T8** is **three times** more important than the technological capability **T5** with respect to the product feature **P8.** In other words, for the purpose of addressing **P8**, **T8** would be three times more helpful than **T5.**



The number one in a paired-wise comparison means that two comparing factors are equally important with respect to a certain criterion. Also, the experts might have no comment on whether a factor is more important than the other one. In that case, “no comparison” will be chosen.

Paired-wise comparisons for market drivers' prioritization:

With respect to entering the market:

1. Functionalit~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	Performance

With respect to functionality:

1. D7. No harmf~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D8. Effectiv~

With respect to performance:

1. D1. Low cost	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D2. Easy to ~
2. D1. Low cost	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D3. Fast app~
3. D1. Low cost	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D4. Durabili~
4. D1. Low cost	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D5. Maintain~
5. D1. Low cost	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D6. Uniformi~
6. D2. Easy to ~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D3. Fast app~
7. D2. Easy to ~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D4. Durabili~
8. D2. Easy to ~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D5. Maintain~
9. D2. Easy to ~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D6. Uniformi~
10. D3. Fast app~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D4. Durabili~
11. D3. Fast app~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D5. Maintain~
12. D3. Fast app~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D6. Uniformi~
13. D4. Durabili~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D5. Maintain~
14. D4. Durabili~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D6. Uniformi~
15. D5. Maintain~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	D6. Uniformi~

Paired-wise comparisons for product features' prioritization:

With respect to D1. Low cost:

1.	P7. Low weig~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	P12. Size an~

With respect to D2. Easy to apply:

1.	P1. Compatib~	>=9.5	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P7. Low weig~
2.	P1. Compatib~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	No comp.	P12. Size an~
3.	P7. Low weig~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	>=9.5	No comp.	P12. Size an~

With respect to D3. Fast application/drying:

1.	P5. Fast dry	>=9.5	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P7. Low weig~
2.	P5. Fast dry	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P12. Size an~
3.	P7. Low weig~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	No comp.	P12. Size an~

With respect to D4. Durability:

1.	P3. Erosion ~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	P4. Corrosio~
2.	P3. Erosion ~	>=9.5	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P8. Self-hea~
3.	P3. Erosion ~	>=9.5	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P9. Self-cle~
4.	P3. Erosion ~	>=9.5	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P10. Strong ~
5.	P4. Corrosio~	>=9.5	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P8. Self-hea~
6.	P4. Corrosio~	>=9.5	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P9. Self-cle~
7.	P4. Corrosio~	>=9.5	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P10. Strong ~
8.	P8. Self-hea~	>=9.5	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P9. Self-cle~
9.	P8. Self-hea~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	P10. Strong ~
10.	P9. Self-cle~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	No comp.	P10. Strong ~

With respect to D5. Maintainability:

1. P8. Self-hea~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P9. Self-cle~
2. P8. Self-hea~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P10. Strong ~
3. P9. Self-cle~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P10. Strong ~

With respect to D6. Uniformity:

1. P6. Surface ~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P12. Size an~

With respect to D7. No harmful effect

1. P6. Surface ~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P11. Transpa~
2. P6. Surface ~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P12. Size an~
3. P11. Transpa~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	P12. Size an~

Paired-wise comparisons for technological capabilities' prioritization:

With respect to P1. Compatibility with other chemical layers:

1.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T3. High-con~
2.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T5. Chemical~
3.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T10. Nanopar~
4.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T5. Chemical~
5.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T10. Nanopar~
6.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T10. Nanopar~

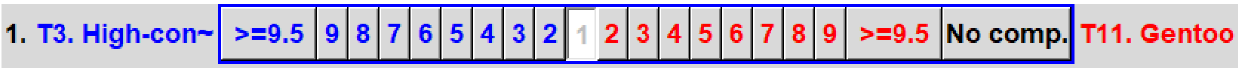
With respect to P2. ARF:

1.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T2. Lubrican~
2.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T3. High-con~
3.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	No comp.	T4. Powered ~
4.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T5. Chemical~
5.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~
6.	T1. Nano/mic~	>=9.5	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T7. Freezing~
7.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T8. Anti-fre~
8.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T9. Plasma t~
9.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T10. Nanopar~
10.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T11. Gentoo
11.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T12. Nanoimp~
12.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
13.	T2. Lubrican~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T3. High-con~
14.	T2. Lubrican~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	>=9.5	No comp.	T4. Powered ~
15.	T2. Lubrican~	>=9.5	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T5. Chemical~
16.	T2. Lubrican~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~

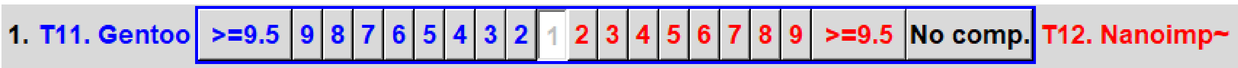
17.	T2. Lubrican~	>=9.5	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T7. Freezing~
18.	T2. Lubrican~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T8. Anti-fre~
19.	T2. Lubrican~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T9. Plasma t~
20.	T2. Lubrican~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T10. Nanopar~
21.	T2. Lubrican~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T11. Gentoo
22.	T2. Lubrican~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T12. Nanoimp~
23.	T2. Lubrican~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
24.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	>=9.5	No comp.	T4. Powered ~
25.	T3. High-con~	>=9.5	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T5. Chemical~
26.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~
27.	T3. High-con~	>=9.5	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T7. Freezing~
28.	T3. High-con~	>=9.5	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T8. Anti-fre~
29.	T3. High-con~	>=9.5	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T9. Plasma t~
30.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T10. Nanopar~
31.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T11. Gentoo
32.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T12. Nanoimp~
33.	T3. High-con~	>=9.5	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
34.	T4. Powered ~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T5. Chemical~
35.	T4. Powered ~	>=9.5	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~
36.	T4. Powered ~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T7. Freezing~
37.	T4. Powered ~	>=9.5	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T8. Anti-fre~
38.	T4. Powered ~	>=9.5	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T9. Plasma t~
39.	T4. Powered ~	>=9.5	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T10. Nanopar~
40.	T4. Powered ~	>=9.5	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T11. Gentoo
41.	T4. Powered ~	>=9.5	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T12. Nanoimp~
42.	T4. Powered ~	>=9.5	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
43.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~
44.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T7. Freezing~
45.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T8. Anti-fre~
46.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T9. Plasma t~

47.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	>=9.5	No comp.	T10. Nanopar~
48.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	>=9.5	No comp.	T11. Gentoo
49.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	>=9.5	No comp.	T12. Nanoimp~
50.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
51.	T6. Ice-phob~	>=9.5	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T7. Freezing~
52.	T6. Ice-phob~	>=9.5	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T8. Anti-fre~
53.	T6. Ice-phob~	>=9.5	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T9. Plasma t~
54.	T6. Ice-phob~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T10. Nanopar~
55.	T6. Ice-phob~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T11. Gentoo
56.	T6. Ice-phob~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T12. Nanoimp~
57.	T6. Ice-phob~	>=9.5	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
58.	T7. Freezing~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T8. Anti-fre~
59.	T7. Freezing~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T9. Plasma t~
60.	T7. Freezing~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	No comp.	T10. Nanopar~
61.	T7. Freezing~	>=9.5	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	>=9.5	No comp.	T11. Gentoo
62.	T7. Freezing~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	No comp.	T12. Nanoimp~
63.	T7. Freezing~	>=9.5	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
64.	T8. Anti-fre~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T9. Plasma t~
65.	T8. Anti-fre~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T10. Nanopar~
66.	T8. Anti-fre~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T11. Gentoo
67.	T8. Anti-fre~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T12. Nanoimp~
68.	T8. Anti-fre~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
69.	T9. Plasma t~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T10. Nanopar~
70.	T9. Plasma t~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T11. Gentoo
71.	T9. Plasma t~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T12. Nanoimp~
72.	T9. Plasma t~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
73.	T10. Nanopar~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T11. Gentoo
74.	T10. Nanopar~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T12. Nanoimp~
75.	T10. Nanopar~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
76.	T11. Gentoo	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T12. Nanoimp~
77.	T11. Gentoo	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
78.	T12. Nanoimp~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~

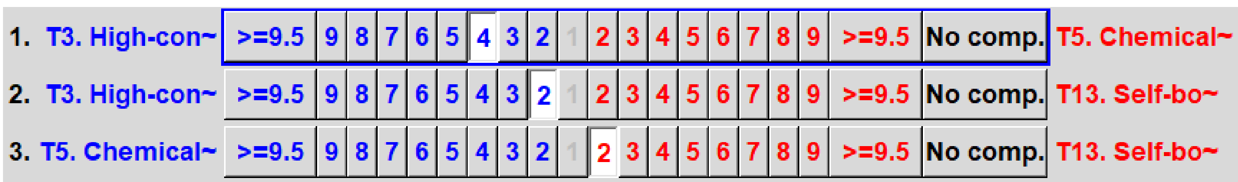
With respect to P3. Erosion resistance:



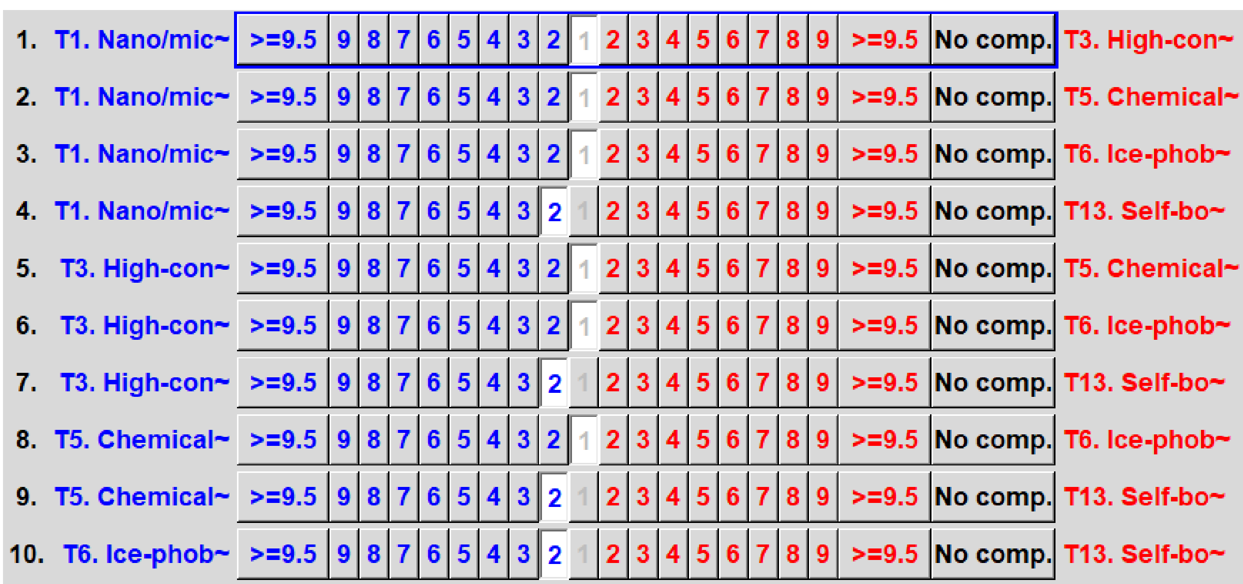
With respect to P4. Corrosion resistance:



With respect to P5. Fast dry:



With respect to P6. Surface uniformity:



With respect to P7. Low weight:

1.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T3. High-con~
2.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T5. Chemical~
3.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~
4.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T9. Plasma t~
5.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T5. Chemical~
6.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~
7.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T9. Plasma t~
8.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~
9.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T9. Plasma t~
10.	T6. Ice-phob~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T9. Plasma t~

With respect to P8. Self-healing:

1.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	>=9.5	No comp.	T8. Anti-fre~

With respect to P9. Self-cleaning:

1.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T2. Lubrican~
2.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~
3.	T2. Lubrican~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~

With respect to P10. Strong adhesion to the blade (mechanical strength):

1.	T11. Gentoo	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	**No comp.**	T13. Self-bo~

With respect to P12. Size and shape:

1.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T3. High-con~
2.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T5. Chemical~
3.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~
4.	T1. Nano/mic~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
5.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T5. Chemical~
6.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~
7.	T3. High-con~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
8.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	>=9.5	No comp.	T6. Ice-phob~
9.	T5. Chemical~	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~
10.	T6. Ice-phob~	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	T13. Self-bo~

Paired-wise comparisons for resources' prioritization:

No comparison was made between the resource allocations with regard to the technological capabilities due to the lack of expert knowledge on the specific fields in the study.

With respect to T1. Nano/microstructured porous material:

1. R1. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	R2. Material~
2. R1. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	R3. Nanomate~
3. R1. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	R6. Ice-phob~
4. R2. Material~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	R3. Nanomate~
5. R2. Material~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	R6. Ice-phob~
6. R3. Nanomate~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	R6. Ice-phob~

With respect to T3. High-conductivity carbon nanotube:

1. R3. Nanomate~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	R4. Mechanic~
2. R3. Nanomate~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	R6. Ice-phob~
3. R4. Mechanic~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	R6. Ice-phob~

With respect to T4. Powered heating:

1. R4. Mechanic~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	R6. Ice-phob~

With respect to T6. Ice-phobic carbon nanotube:

1. R1. Chemical~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	R3. Nanomate~