IT based Framework facilitating Technolgy Roadmapping striving for Sustainability

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IT based Framework facilitating Technology Roadmapping striving for Sustainability

Stefan Kaden, Ralf Isenmann

Zusammenfassung Das aktuell wachsende Bewusstsein für Nachhaltigkeit stellt immer mehr Forschungs- und Entwicklungsbereiche vor die Aufgabe, ihre Innovationsplanung um Aspekte einer nachhaltigen Entwicklung zu erweitern.

Das Technologie-Roadmapping ist eine etablierte Methode für eine komplexe Innovations-planung. Im Rahmen dieser Thesis wurde deshalb untersucht, ob und wie Aspekte der Nachhaltigkeit in diese integriert werden können. Hierzu wurden folgende Forschungsfragen gestellt:

Welche Beispiele für die Integration von Aspekten nachhaltiger Entwicklung in Technologie Roadmaps lassen sich heute schon finden und wie wurden diese realisiert?

Auf welche Art kann ein IT-Framework das Technologie-Roadmapping unterstützen und die Integration von nachhaltiger Entwicklung ermöglichen?

Die erste Forschungsfrage wurde mittels einer systematischen Literaturrecherche untersucht. Dabei konnte aufgezeigt werden, dass Nachhaltigkeit im Technologie-Roadmapping häufig nur alleinstehend betrachtet wurde. Die Integration als gleichbedeutende Perspektive führte durch gegenseitige Abhängigkeiten zu bestehenden Perspektiven zu einer stark erhöhten Komplexität. Die wenigen dazu gefundenen Beispiele lösten diese Komplexität entweder mit einer ebenso steigenden Teamgröße oder einer zunehmenden Automatisierung von Arbeitsschritten.

Im Rahmen der zweiten Forschungsfrage wurden daher Software-Tools für nachhaltige Entwicklung und zur Unterstützung des Technologie-Roadmappings gegenübergestellt. Die zugrundeliegenden abstrakten IT-Konzepte wurden dann zur Beschreibung drei unter-schiedlicher Szenarien und Frameworks benutzt. Diese spiegeln die unterschiedlichen Voraussetzungen im Unternehmen aufgrund variierender Daten- und Software-Standardisierung wider.

Es wurden so mehrere Wege aufgezeigt, wie der Prozess des Technologie-Roadmappings durch bereichsübergreifende Kooperation sowie asynchroner und automatisierter Informationsverarbeitung und -zentralisierung um Aspekte nachhaltiger Entwicklung erweitert wer-den kann. Abschließend werden Vor- und Nachteile der auf diese Weise realisierten Verlagerung der Komplexität vom Roadmapping-Prozess zur IT-Architektur aufgezeigt.

Keywords: Nachhaltige Entwicklung, Technologie Roadmapping, IT-Framework, Digitalisierung, Software-Tools

Abstract With today's growing awareness on sustainability, various R&D management departments are given the complex task to implement sustainability as an additional focus to their innovation planning. With technology roadmapping, a well-known tool for innovation planning in general, the questions remain, if and how technology roadmaps are suited to implement sustainability aspects among the already existing perspectives. Therefore, the main questions of this thesis are:

Which examples of sustainability integrations in technology roadmaps can already be found and in which possible ways are these integrated into technology roadmaps?

How can an IT Framework facilitate technology roadmapping and the implementation of sustainability?

Starting with a preceding literature review for the integration of sustainable development in technology roadmapping, a defined terminology is used to investigate into the current state of research. Based on this, a subsequent classification of the extend and approaches in which sustainability is currently included into technology roadmaps is used to identify that, for the most part, found technology roadmaps lack a complex integration of sustainable development. In the few exceptions to this finding, the complexity is handled either by exceeding numbers of involved people or by a rising degree of automation of work steps.

To investigate further in the second research question, a synopsis of current IT tools for technology roadmapping and for sustainable development planning is used to systematically review facilitation potentials. The corresponding concepts are then integrated in three different IT frameworks which represent varying preconditions and requirements of existing corporate IT landscapes. It was shown, how the process of technology roadmapping can be facilitated in general and to include aspects of sustainable development through cross-departmental cooperation as well as asynchronous and automated information processing and centralization.

Concluding, advantages and disadvantages of the resulting shift of complexity from the process of roadmapping towards a more complex IT framework are explained.

Keywords: sustainable development, technology roadmapping, IT framework, digitalization,
software tools

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Abbreviations

AHP	Analytical Hierarchy Process
API	Application Interface
CPU	Central Processing Unit
CSV	Comma Separated Values, also used as file extension: *.csv
EAI	Enterprise Application Integration
EHS	Environment, Health and Safety
ERP	Enterprise Resource Planning
FTP	File Transfer Protocol
GPU	Graphical Processing Unit
GUI	Graphical User-Interface
HTTP	Hypertext Transfer Protocol
IEEE	Institute of Electrics and Electronic Engineers
IT	Information Technology
KPI	Key Performance Indicator
QFD	Quality Function Deployment
R&D	Research and Development
REST	Representational State Transfer
SD	Sustainable Development
SFD	Stock and Flow Diagramm(s)
SLR	Systematic Literature Review
SOAP	Simple Object Access Protocol
TRM	Technology Roadmap(s)[1]
UI	User-Interface
XML	Extensible Markup Language, also used as file extension: *.xml

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[1] The term „technology roadmapping“, which rather corresponds to the process of the creation of technology roadmaps, is always written out.

1 Introduction: Integration of Sustainability in Technology Roadmapping

Recent elections of the European Parliament have shown that the awareness of our society regarding sustainability is growing evidently (Graham-Harrison, 2019). The political parties are put under pressure to enforce regulations towards a more sustainable future and as a result, regulations and threshold values become way more strict (European Comission, 2019).

Companies not only have to adapt their products rapidly to meet the requirements of the regulation, but also to meet moral expectations of society, which are often even higher and predominantly unseizable. As another important factor within this context, the increasing influence of economy on society results in an increasing influence of society on the economy reversely. Exposed to the public observation due to medial focus and globalization, companies not only have to create products that meet the functional customer demand, but also have to answer the question of what the product is made of and how it was produced in accordance with moral and legal requirements (Sandner, 1992, pp. 205–228).

Accordingly, the various R&D management departments are given the complex task to implement sustainability as an additional focus to their innovation planning. As well-known tools to perform the task of innovation planning in general, technology roadmaps (TRM) are set up to control a technology to the right time and degree of maturity according to the target market and the company's strategy (Phaal, Farrukh, & Probert, 2001).

However, the question remains if and how technology roadmaps are suited to implement sustainability aspects among the already existing perspectives like technology, regulation, and market. Therefore, the main questions of this thesis are:

Which examples of sustainability integrations in technology roadmaps can already be found and in which possible ways are these integrated into technology roadmaps?

How can an IT Framework facilitate technology roadmapping and the implementation of sustainability?

Following in the next sections, these questions are further examined. Starting with a preceding literature review, a defined terminology of technology roadmaps and sustainable development is used to investigate into the current state of research. The findings will then form the base for the classification of the extend and approaches in which sustainability may be included into technology roadmaps. Subsequently, a synopsis of software tools for technology roadmapping and for sustainable development planning will be used to systematically examine the current state of facilitation potentials and corresponding concepts of relevant IT tools. Concludingly, these concepts will be abstracted and integrated into conceptual IT frameworks to facilitate technology roadmapping striving for sustainability.

2 Basic Terms and Concepts to Sustainability in Technology Roadmapping

To examine the status quo of sustainable development in technology roadmapping, the concepts and terms are explained first. Afterwards, a preceding literature review is summarized, and its conceptual results are explained. These results will then be incorporated into the concepts in the following section 3.

2.1 Integration of Sustainability Issues in Technology Roadmapping and Technology Roadmaps

Focusing on the first research question, a common understanding of the respective terms *technology roadmaps* and *sustainable development* is established in this section.

2.1.1 Definition of Technology Roadmapping and Technology Roadmaps

The use of roadmapping as a systematic management method was first commonly introduced in the late 1970s by Motorola and Corning. In general, roadmaps are used to enable the exploration of different perspectives on a chronological basis and as well point out interrelations of these perspectives which lead to discontinuities in their development path. The most common form of a roadmap can be described as a “time-based chart, comprising a number of layers that typically include both commercial and technological perspectives.” (Phaal, Farrukh, & Probert, 2004, p. 10)

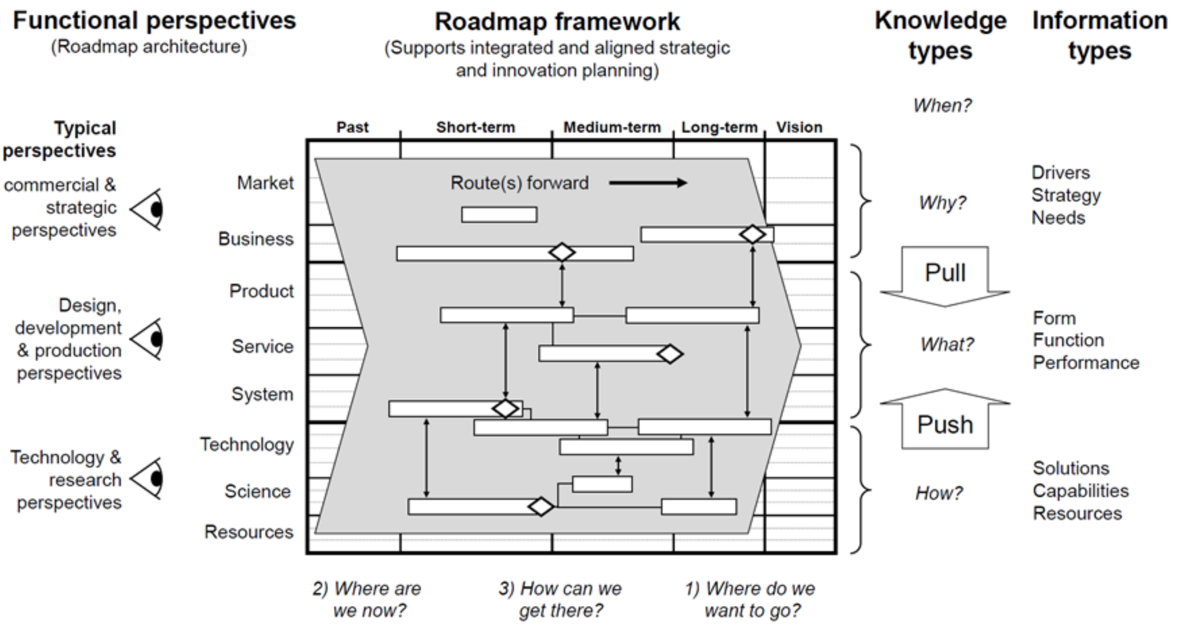

Figure 1 Generalized technology roadmap structure (Moehrle, Isenmann, & Phaal, 2013, p. 20)

However, the term *technology roadmapping* can be interpreted in two ways: (Moehrle et al., 2013, p. 4)

- In a **narrow sense**, technology roadmapping only refers to those roadmapping activities, that focus on product-, process- or service-technologies, leaving out pure product, project, or function roadmaps without this stringent focus on technology
- In a **broader sense**, all roadmapping activities that include technology, even by very incidental means, are concerned.

As the main question of this research project is about how sustainability may be implemented in technology roadmapping by general means, the broader definition is used. This implies, that roadmaps are included which would be specified without the technology prefix when using the narrow definition. The generic format of a technology roadmap is depicted in Figure 2.

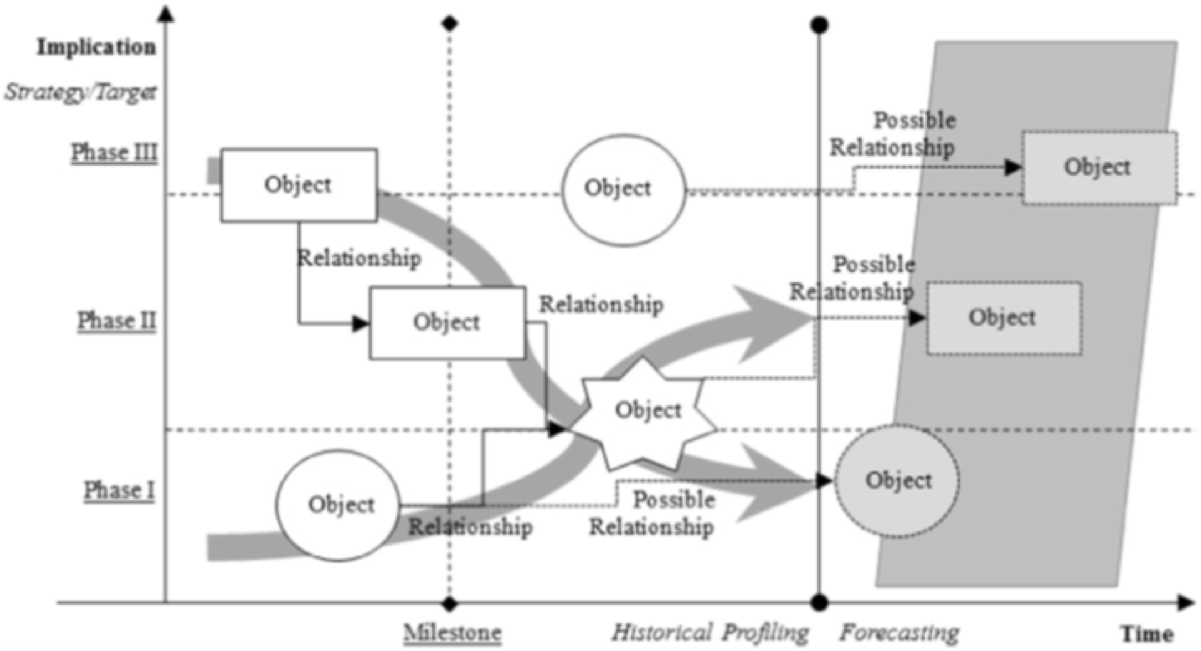

Figure 2 General format of technology roadmapping (Y. Zhang et al., 2016)

For later categorization of technology roadmaps, key aspects are deviated from generic technology roadmaps: (see Figure 1, Figure 2)

- **Artefacts** (or objects) are the key items of the TRM that describe for example (groups of) technologies, regulations or events and are connected in a certain relationship logic to depict a progression. They appear in different shapes and are further explained by a varying degree of information, ranging from solely technology-names or pictures up to full technical specifications given to each artefact.
- **Perspectives** describe the primary arrangement logic of artefacts (or example technology, product and market). As seen in Figure 1, certain superordinate perspectives like “technology & research perspectives” may be further broken down into sub-perspectives like “Technology”, “Science” and “Resources”. Instead of the term “perspectives”, certain sources using the term “layers” and “sub-layers” as a deduction of a certain two-dimensional expression of TRM (Phaal et al., 2004, p. 14).
- **Goals** describe the overarching vision of the TRM and may therefore be described as artefacts in the “vision” or “objective” section within the roadmap (see Figure 52). They describe the targeted future status and may also be left out in the TRM itself to rather be described in the text that comes along the publication.

As there is a vast amount of different kinds and applications, the term technology roadmap is further narrowed down for this research project by the definition of Phaal et al. (2004) given above. The aspect of a time-oriented interrelation of different perspectives, depicted in some kind of a chart is commonly found in different sources and will therefore be used as the primary sampling criterion (Sungjoo Lee & Park, 2005; Phaal et al., 2004; Y. Zhang et al., 2016).

This implies the exclusion of roadmaps that are formed as a text, lack sequential artifacts (e.g., objects resulting out of relations to previous ones) or do not examine inter-perspective-correlations (e.g., defining sustainable development on the basis of technology and completely leaving out legal, political and economic aspects)

2.1.2 Classification of Technology Roadmaps

In their publication "Technology roadmapping - A planning framework for evolution and revolution", Phaal et al. provide an overview of technology roadmapping as a method of technological foresight and as well give a generalized classification for technology roadmaps by three main characteristics: purpose, format and use. Furthermore, they clustered the two aforementioned into 16 types of technology roadmaps, which is depicted in Figure 3 (Phaal et al., 2004, p. 11).

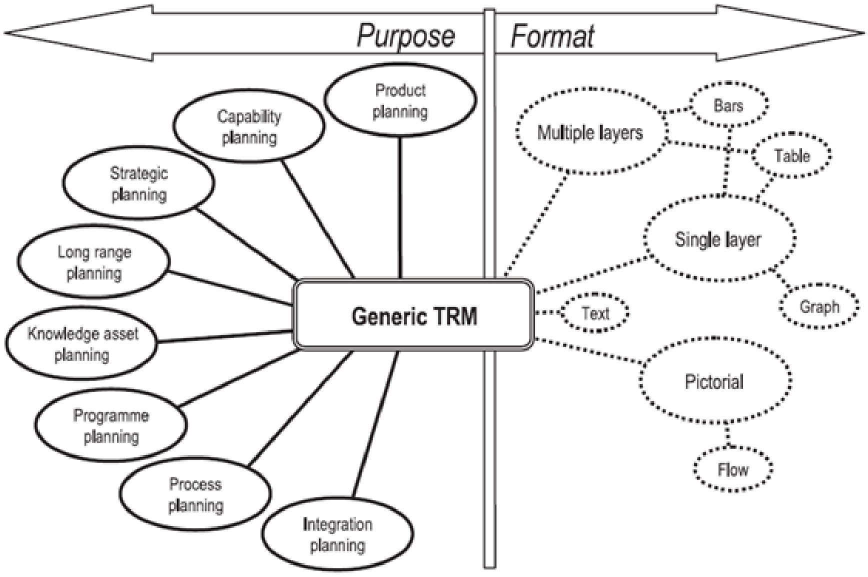

Figure 3 Characterization of roadmaps: purpose and format (Lowe, 1995; Phaal et al., 2004)

By means of "purpose", technology roadmaps are clustered into eight types by their focused field of application: (Phaal et al., 2004, pp. 13-14)

a) **Product planning**: integrating technology into certain generations of (often manufactured) products

b) **Service/capability planning**: integrating technology as a support for organizational capabilities

c) **Strategic planning**: creating a future vision and current position to define transition paths from different perspectives and highlight gaps

d) **Long-range planning**: a more abstract and far-ranging consideration of technology development paths to identify potentially disruptive movements

e) **Knowledge asset planning**: defining transition paths from knowledge assets to business objectives by knowledge management initiatives

f) **Program planning**: integrating strategic objectives and technology developments into project planning

g) **Process planning**: management of knowledge assets in a certain focused area

h) **Integration planning**: integration of technology into products or systems by means of different degrees of product maturity (also used for technological evolution)

These TRM purpose types are depicted in Figure 4.

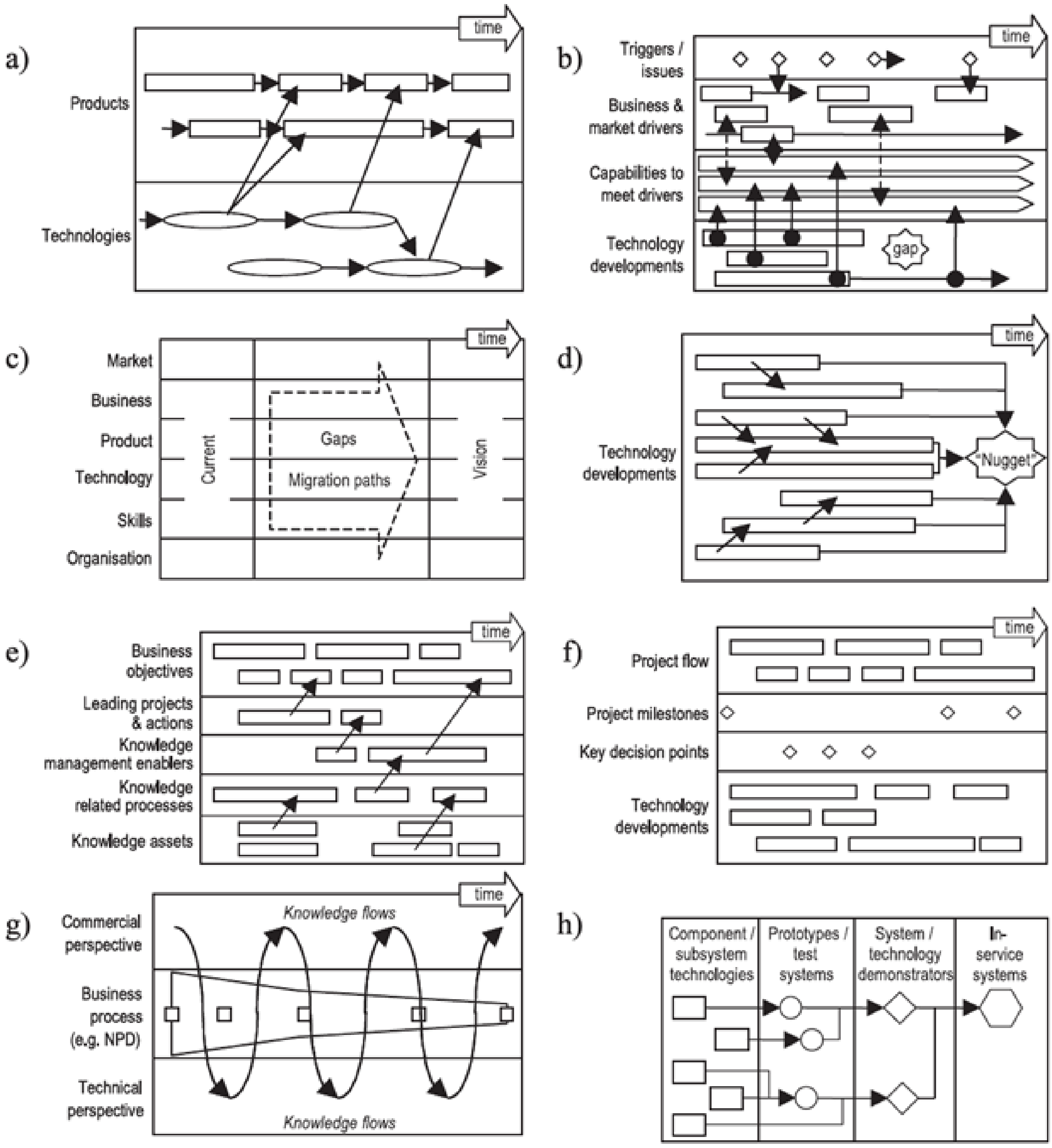

Figure 4 Purpose examples of technology roadmap types (Phaal et al., 2004, p. 12)

The integration of sustainability may concern all of the above-mentioned types and corresponding purposes. As the classification according to these eight types is not suited to carve out different integration approaches, it is not used in the context of this research project.

In the second class by means of “format”, technology roadmaps are clustered according to their visual appearance into eight types: (Phaal et al., 2004, pp. 14–15)

a) **Multiple layers**: combining a number of layers (or “perspectives”, see section 2.1.1) and artefacts and depicting a technological or product/system-evolution within and/or across the layers

b) **Bars**: simplified version of a) by reducing/omitting the relations across layers and unifying the form of all artefacts

c) **Tabular**: focusing on development/evolution of (often quantified) properties to fixed states of time/maturity degrees and omitting visual relationships

d) **Graphs**: arranging features, that are fully quantified or measurable by a scale, on a two- or three-dimensional graph

e) **Pictorial**: visualizing a technology development/integration in a context-oriented and often metaphorical way to support the understanding of transition paths

f) **Flow chart**: simplifying the relationship of visions, measures and outcomes in a one-dimensional way

g) **Single layer**: simplified version of a) by only examining one layer

h) **Text**: written description of any of the other TRM-types.

The first six types are depicted in Figure 5, leaving out the single layer type as a sub-type of a) and the text type.

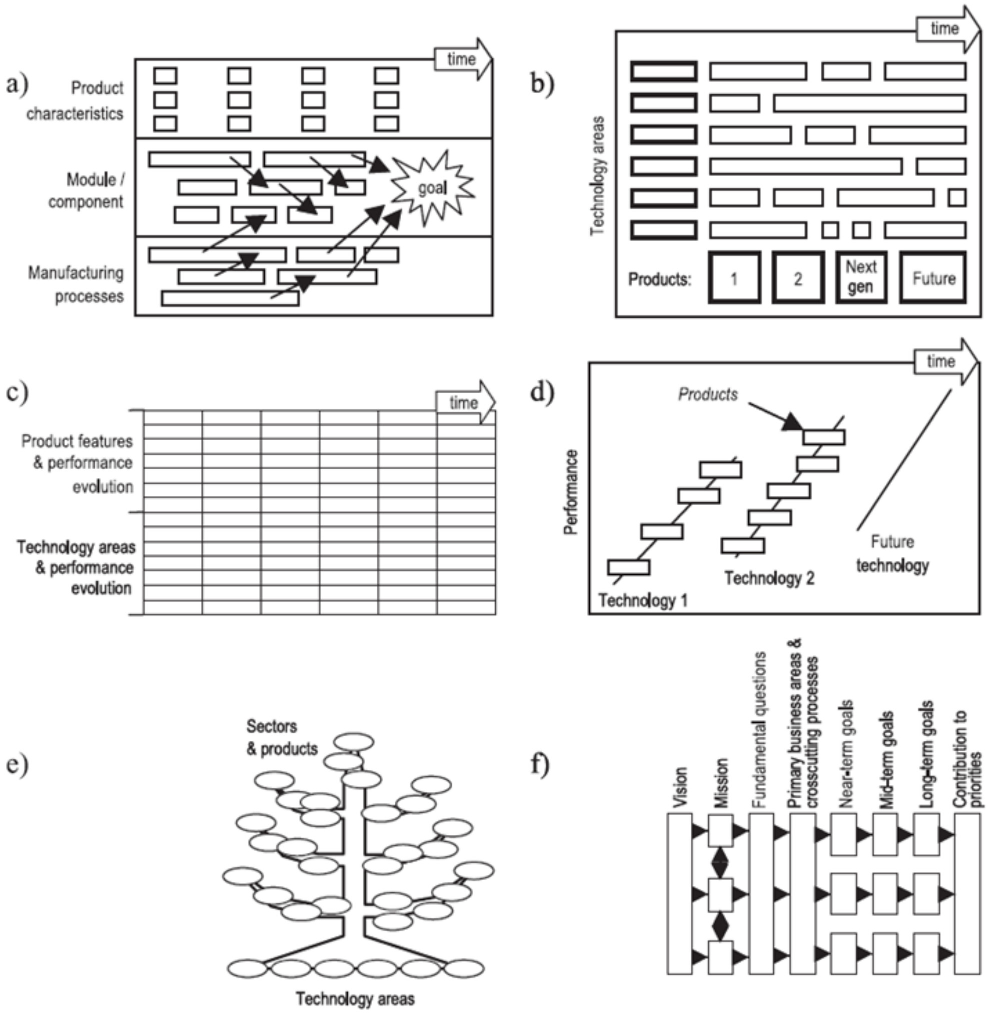

Figure 5 Format examples of technology roadmap types (Phaal et al., 2004, p. 13)

The visual arrangement of artefacts is the result of a sufficient information base by means of quantified or qualitative facts and relationships. In that way, the given TRM-types implicate a varying degree of creative leeway in terms of structural restrictions of visualizing relationships, extensibility for additional perspectives and necessary quantification of artefacts and goals regarding their properties. This implication exerts a considerable influence on the effort needed to create a certain type of TRM, as complexity grows exponentially with a rising number of examined perspectives and relationships in certain types.

In contrast to the purpose-oriented classification, the format-orientation allows drawing conclusions about the integration depth of sustainability regarding the varying quantitative or qualitative description of artefacts and relationships to other perspectives. Therefore, a formal classification is integrated into the examination by the description of artefacts and by the descriptions of perspectives and relationships (see section 2.2.2).

2.1.3 Definition of Sustainable Development

The term *“Sustainable Development”* itself links the idea of preserving the earth for future generations with the concept of development in a very broad sense, which might also be the reason why it has been coined very differently. The idea of sustainable development “*can be traced back at least as far as the mid-1960s, when appropriate technology was promoted as the way to help develop the lesser developed countries*.” (DuBose, 1995)

However, the basis for the current use of the term was given in 1987 by the World Commission on Environment and Development (WCED) or more commonly known as the Brundtland Commission. It defined sustainable development as a “*development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*” (Lebel & Kane, 1987)
This definition implies two concepts: (Mebratu, 1998)

1st Concept:	Fulfilling the needs of the current generation, especially of “unprivileged” or poor people
2nd Concept:	Limited environmental capability of fulfilling the future needs imposed by the current society which uses a certain state of technology

While the 1st concept is describing the current state of global development in general, the 2nd concept adds the aspect of sustainability to it. According to the idea of innovation for sustainability, an intentional change to an organization’s philosophy is needed to do so. In this context, the targets of a business are classified into more dominant and less dominant ones (Bocken, Ritala, Albareda, & Verburg, 2019).

In this thesis, the term of sustainable development is given by the definition of the Brundtland Commission and furthermore described as the coexistence of sustainability as a dominant target of development among others (e.g., economical ones).

2.2 Insights and Findings based on the systematic Literature Review to Sustainability in Technology Roadmapping

Given a common definition of technology roadmaps and sustainable development, the first research question is now to be examined in this section. To investigate the current status of *if* and *how* sustainability is to be implemented into TRM, a systematic literature was conducted.

2.2.1 Procedure of the systematic Literature Review

Three databases[2] were systematically scanned and filtered for TRM with integrated aspects of sustainability. Due to the amount of literature found in the included databases, the total number considered in this thesis had to be limited to a number that is practically manageable (Okoli & Schabram, 2010). Therefore, a contend-oriented and a research design-oriented selection of the literature was done, while still matching the criterion that the review maintains comprehensible.
Criteria for a content-oriented selection of sources are, for example: (Fink, 2009, pp. 59–60)

- Content: Limitation on sources that are related to the research question
- Publication Language: Limitation on sources that are written in certain languages that are known to the reviewer
- Access: Limitation on sources for which the reviewer has access on
- Date of publication: Limitation on sources of a certain range of publication

The choice and definition of these or other criteria remains at the subjective discretion of the reviewer. Thus, an explicit definition of applied criteria is needed to maintain the reproducibility of the review (Okoli & Schabram, 2010).

The criteria for the research given in the tables below were chosen according to the research question. However, the critical point about that question is neither to find out nor to categorize the explicit content of roadmaps concerning sustainable development, but rather about to extract and review **implementation methods** of sustainable development in technology

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[2] Databases: ScienceDirect (www.ScienceDirect.com), SpringerLink (www.link.springer.com), IEEE Xplore (www.ieeexplore.ieee.org)

roadmaps on an abstract level. Accordingly, the in- and exclusion criteria aim for visual roadmaps that examine the topic in a multi-dimensional way. For example, this results in non-inclusion of the publication date as a criterion - although commonly used to exclude older articles - because of the missing causal correlation of it with the abstract implementation method. The quantitative in- and exclusion criteria are the following, numbered for later reference.

Table 1 Practical Inclusion Criteria

ID#	Inclusion Criteria	Type
I1	Terms with either “Sustainable Development” or “Sustainability” together with “Technology Roadmap” found in contents and Meta-Data of the article[3]	Content
I2	Term “Roadmap” in title	Content
I3	Articles written in English or German	Language
I4	Articles with visual roadmaps (e.g., see Figure 2) or tabulated roadmaps	Content

Table 2 Practical Exclusion

ID#	Exclusion Criteria	Type
E1	Solely textual descriptions of roadmaps	Content
E2	Articles with Roadmaps that have no context of Sustainability	Content
E3	Inaccessibility of articles due to paid-access or unavailability for university-access	Access
E4	Articles that reflect a personal opinion, e. g., comments or letters	Content

In the first step, all databases were searched for criteria I1 by including all articles concerning sustainable development and technology roadmaps. At this point, the access exclusion criteria E3 was applied as well. The remaining pool were narrowed down considerably by applying criteria I2 and leaving out all articles without the term “roadmap” in title. This had to be done due to high number of articles found as well as the very common usage of the term “roadmap” in different contexts. Random samples during the research showed that by exclusively

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[3] Boolean search term: (“Sustainable Development” OR “Sustainability”) AND “Technology Roadmap”

scanning for articles with “roadmap” in title, the probability of having technology roadmaps in the needed visual kind (see section 2.1.1) was greatly improved. Additionally, articles that lack the correct form (E4) were left out as well as those that lack any reference to roadmaps in their abstract. The 250 articles left are then downloaded to be reviewed for the other in- and exclusion criteria (see Figure 6).

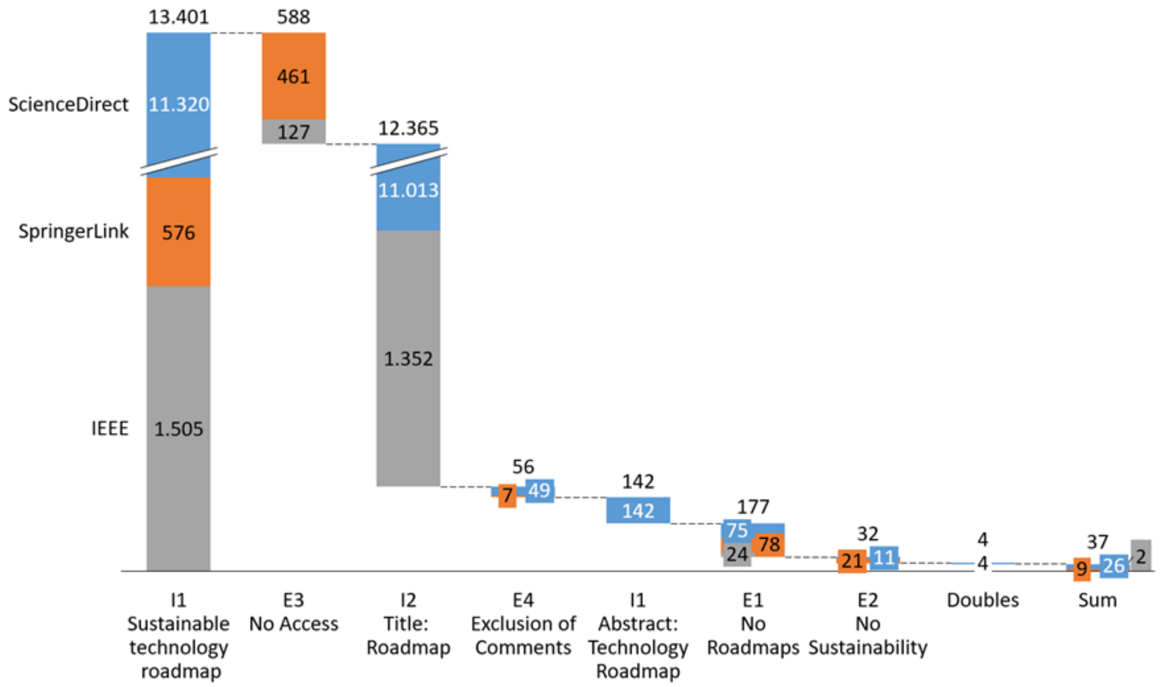

Figure 6 Selection-process as part of the database search (Source: Personal collection)

By manually scanning the remaining articles, the criteria were applied. A first finding was that even though all articles needed to have any reference to “Technology Roadmaps”, still a considerable number of articles lacked any visual or tabulated roadmap and rather describe the technology paths in a textual or qualitative way.

After having quantitative criteria applied, the content of the remaining 37 articles now had to be reviewed in more detail to apply qualitative criteria. These criteria helped to categorize the approach the researchers were taking to implement sustainability into a technology roadmap.

2.2.2 Content and Complexity Classification of Technology Roadmaps based on Implementation of Sustainable Aspects

The pool of remaining articles was further examined by a screening for quality. In general, to select studies which were scientifically well designed to achieve their objectives, following criteria are consulted: (Fink, 2009, p. 63)

- Internal and external validity of the research design

- Reliability and validity of data sources
- Appropriate analytical methods for the characteristics and data of the study
- Significance in practical or statistical terms

These criteria mentioned above served as a binary filter, e.g., if an article did not meet or failed to prove the compliance to one of these, it was taken out of the consideration. Taking a closer look to the examination on the criteria of Fink, 2009), it becomes evident that they are aimed for quantitative studies rather than conceptional work that rely on theory or model building, as the differentiation of research design is only made between experimental or observational (Fink, 2009, p. 63)

However, to select applicable qualitative criteria for the systematic literature review, Okoli and Schabram (2010, p. 28) proposed a critical examination of reasoning for qualitative theoretical articles, which covers four items:

- Claims: What statements are made in the article?
- Evidence: Is there a comprehensible reasoning for these claims?
- Warranty: Is the evidence backed up by other sources?
- Backing: What kind of sources were used to back up the reasoning?

Consecutively, these criteria were adapted to the focus of the literature review:

Table 3 Qualitative Criteria

#	Qualitative Criteria	Type
Q1	In which way sustainability is integrated into the technology roadmaps?	Claims
Q2	Which kind of artefacts are integrated into the technology paths?	Claims, Evidence
Q3	Are artefacts described in a qualitative way or further specified by quantitative properties?	Warranty, Backing
Q4	Which perspectives are examined?	Claims, Evidence
Q5	How are technology paths associated?	Evidence, Warranty

Rather than narrowing down the remaining articles, these criteria served as the basis for classification of the TRM, especially regarding the complexity and integration of sustainable aspects. As this complexity is playing a central role in the following examination of facilitation potential of technology roadmapping by IT, the content classification criteria derived from these qualitative criteria are briefly explained. The corresponding TRM images can be found in Appendix A - Referenced Pictures of found Technology Roadmaps.

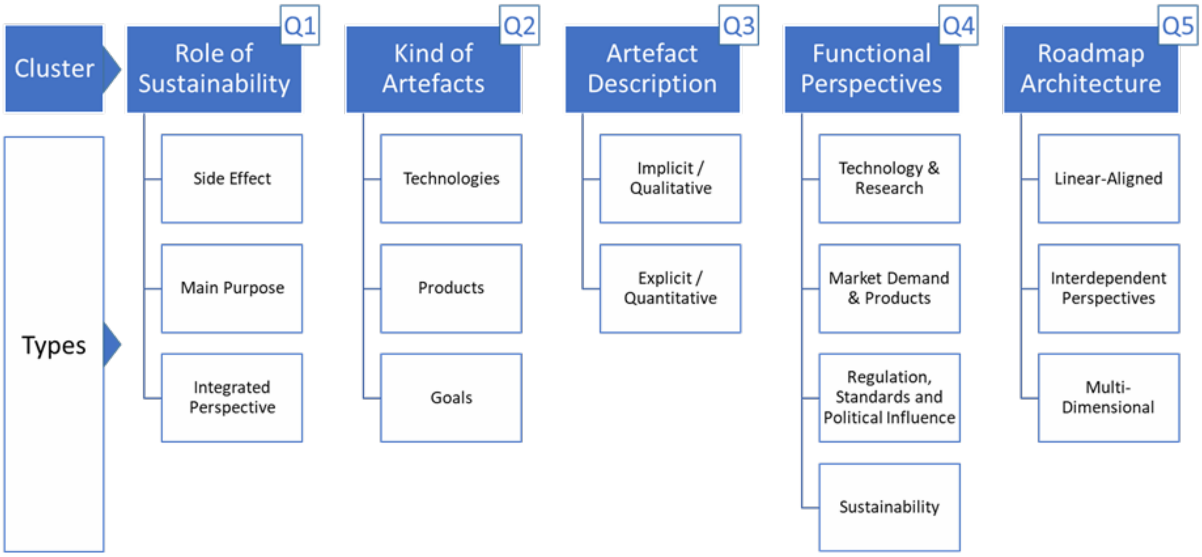

Figure 7 Classification of TRM according to qualitative and formal criteria (Source: Personal collection)

Q1. Role of Sustainability

The articles were first scanned for the method of integrating sustainability into the technology roadmap in criteria Q1. This was done to differentiate if sustainability was examined in the roadmap as

Q1a. **just a side effect** of the general improvements of products and technologies, for example the development of fully automated assistive robotics (Gerdsri, Puengrusme, Vatananan, & Tansurat, 2019), which might result in a more sustainable manufacturing due to a higher energy efficiency and less consumption of electricity in manufacturing[4], though the sustainable aspect is not especially focused,

Q1b. **the main or only purpose** of the whole TRM, for example the roadmap to a more sustainable method of cattle farming, (Gallegos Rivero & Daim, 2017) which might as well dissent with the economic plans of companies and therefore includes no statement of how feasible a realization is,

Q1c. **an integrated perspective** among others or **within existing perspectives** as an integrated property, for example a technology roadmap for a more advanced construction development which links different projects to, among others, sustainability and

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[4] However, these efficiency increases are often compensated by higher consumption or demand, which is described by the “rebound effect” Pfriem et al. (2006, p. 22)

integrates environmentally friendly materials as a separate perspective. This is depicted in Figure 52, Figure 53 and Figure 54 (Kim et al., 2009).

The order of these three categories is derived from a rising complexity of integrating the perspective “sustainability” into the technology roadmap. While sustainability as a side-result of improved technology is still a step towards a more environmentally friendly technology planning, a considerable additional effort must be taken into account to exploit the full potential of an integrated sustainability perspective in which sustainability is as important as other perspectives.

Q2. Kind of Artefacts

Another classification of the roadmaps was done by the type of artefacts that were used. In this context, three different artefact kinds were differentiated for criteria Q2:

Q2a. **Technologies**, optional with further textual description or quantitative characteristics (see Figure 55). These artefacts correspond to technical solutions, often without a specific product or use case.

Q2b. **Products**, optional described by their properties or included technologies (see Figure 56). These artefacts describe the purpose of use for technologies.

Q2c. **Goals** and standards, optional described by quantitative thresholds or legislative references. These artefacts are used to describe a certain vision (or approach to achieve this vision) or necessary regulative compliance (see Figure 57 and Figure 58).

Q3. Artefact Description

Beside the classification of artefacts on the basis of their kind, another distinction was made regarding their description by means of criteria Q3:

Q3a. **Implicit or qualitative** descriptions of artefacts are most common among the found technology roadmaps (see Figure 60)

Q3b. **Explicit or quantitative** descriptions can point out a development of key performance indicators (see Figure 59) or highlight technical standards, that have to be met at a certain time (see Figure 61)

Both description types can be applied to any artefact kind.

Q4. Implemented Functional Perspectives

By means of criteria Q4 and Q5, the roadmaps are classified according to their examined perspectives and their interrelations. Starting with Q4, four different functional perspectives that appeared in the TRM were distinguished:

Q4a. **Technology & Research**: Mainly as a push-factor, this perspective forms the basis for the products or services to be developed (see Figure 62)

Q4b. **Market Demand & Products**: As a pull factor, artefacts of this perspective require technologies to achieve a certain maturity before they can be provided to the market (see Figure 64)

Q4c. **Regulation, Standards & Political Influence:** This perspective can serve both as a push factor, when it comes to subsidies of new technologies or as a pull factor, when it comes to penalties and bans of old ones (see Figure 63).

Q4d. **Sustainability:** Following the research question, this perspective was added to the distinction. Usually, sustainability will serve as a pull-factor in alliance with market- or legislative demands (See eco-efficiency in Figure 65).

Other perspectives beside these four were excluded from the distinction as they were less commonly found and, in most cases, very specific to the examined roadmaps.

Q5. Roadmap Architecture

The roadmap architecture was also classified by criteria Q5, in which the interrelation of the perspectives or technology paths were distinguished with rising complexity as following:

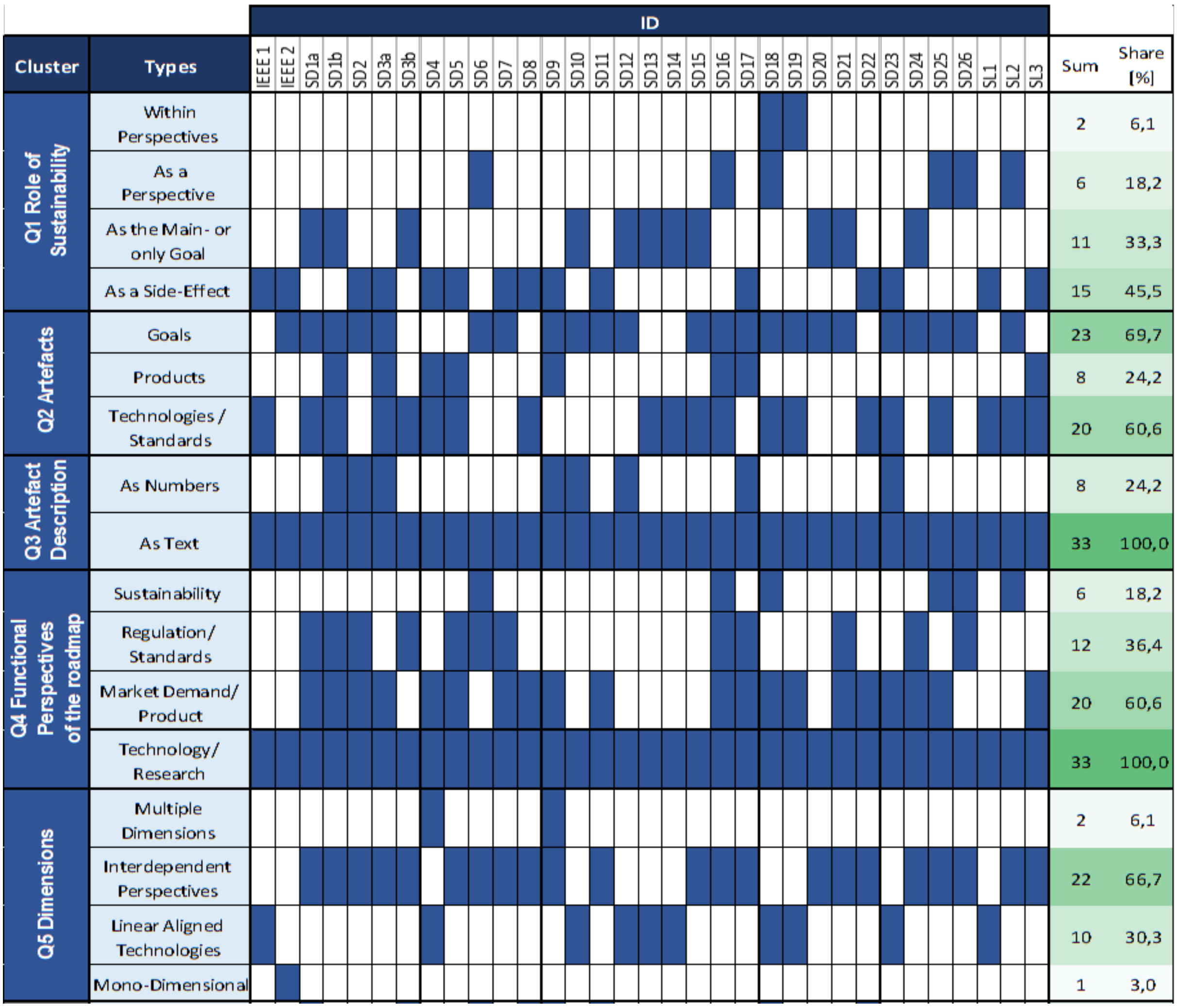
Q5a. **Linear-Aligned** roadmaps consist of perspectives with possibly sub-categories or products which are dependent on a single dimension, which is usually time, but lack interdependencies (see Figure 67). This correlates with the “bar”-type in Figure 5.

Q5b. Roadmaps with **interdependent perspectives** include technology paths, that are linear-aligned and include interdependencies (see Figure 68). In some cases, the time dependence of the roadmap is exchanged for another technological dimension, like a manufacturing process of CMOS devices as seen in Figure 69.

Q5c. **Multi-Dimensional** Roadmaps add symbols, colours or other measures to the roadmap architecture to extend the information density of technology paths, like technology importance and individual developing strategies as seen in Figure 70.

With these criteria, the articles (abbreviated into identifiers according to their source database) were listed and classified in a table. In Table 4, the results[5] are depicted followingly.

Table 4 Final classification result (Source: personal collection)



		ID																																
Cluster	Types	IEEE 1	IEEE 2	SD1a	SD1b	SD2	SD3a	SD3b	SD4	SD5	SD6	SD7	SD8	SD9	SD10	SD11	SD12	SD13	SD14	SD15	SD16	SD17	SD18	SD19	SD20	SD21	SD22	SD23	SD24	SD25	SD26	SL1	SL2	SL3	Sum	Share [%]
Q1 Role of Sustainability	Within Perspectives																						■	■											2	6,1
	As a Perspective										■										■		■							■	■		■		6	18,2
	As the Main- or only Goal			■	■			■							■		■	■	■	■					■	■			■						11	33,3
	As a Side-Effect	■	■			■	■		■	■		■	■	■		■						■					■	■				■		■	15	45,5
Q2 Artefacts	Goals		■	■	■	■	■				■	■		■	■	■	■			■	■	■	■	■	■	■		■	■	■	■		■		23	69,7
	Products				■		■		■	■				■							■	■												■	8	24,2
	Technologies / Standards	■		■	■		■	■	■	■			■					■	■	■	■		■	■			■	■		■		■	■	■	20	60,6
Q3 Artefact Description	As Numbers				■	■	■							■	■		■					■						■							8	24,2
	As Text	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	33	100,0
Q4 Functional Perspectives of the roadmap	Sustainability										■										■		■							■	■		■		6	18,2
	Regulation/ Standards			■	■	■		■		■	■	■									■	■				■			■		■				12	36,4
	Market Demand/ Product			■	■	■	■		■	■		■	■	■		■					■	■	■	■		■	■	■	■	■				■	20	60,6
	Technology/ Research	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	33	100,0
Q5 Dimensions	Multiple Dimensions								■					■																					2	6,1
	Interdependent Perspectives			■	■	■	■	■		■	■	■	■	■		■				■	■	■			■	■	■		■	■	■		■	■	22	66,7
	Linear Aligned Technologies	■							■						■		■	■	■				■	■				■				■			10	30,3
	Mono-Dimensional		■																																1	3,0

The sum of applicable TRM for each type is calculated and inserted into the right side of the table (see Table 4, “Sum”), together with the share of that number in relation to the entirety of TRM (see Table 4, “Share [%]”). Given this distribution, statements can already be made regarding the different clusters.

Regarding the role of sustainability, nearly 80% of all TRM included a non-integrated sustainability aspect by means of either a resulting side effect (see Q1a with 46%) or as the only motivation to create that TRM (see Q1b with 33%). This distribution shows that there seems to be either methodological difficulties to implement sustainability as a tantamount perspective

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[5] For the full list with written out titles and sources, see Appendix B - List of found Technology Roadmaps.

or that there is a discrepancy in the way of how sustainability-based regulation affects product development and how well ecologic aspects, by means of quantified properties, are actually integrated into technical R&D plans (See section 1).

This is also expressed by the integration of sustainability in terms of perspectives (cluster Q4) and artefact description (cluster Q3): not a single TRM that integrated sustainability as a perspective or within those, also described artefacts in a quantified way (see Q3b), while 24% of all TRM did. Viewed differently, out of eight TRM that actually described artefacts in a quantified way, five included sustainability just as a side effect of the general technological development.

2.2.3 Methodological Classification of Technology Roadmaps based on Automation of Technology Roadmapping

Referring the research question of *how* sustainability can be integrated in technology roadmapping, the given possible solution approaches of the found roadmaps are now classified systematically by a rising degree of automation.

a) Manual Integration of Sustainability by Goals

As an example for a manual integration of sustainability, the TRM developed by Haddad and Uriona Maldonado (2017) is used (see Figure 71). This TRM is the result of a process that involved several workshops of "*a pool of 60 plus experts from industry and academia*" (Haddad & Uriona Maldonado, 2017, p. 255):

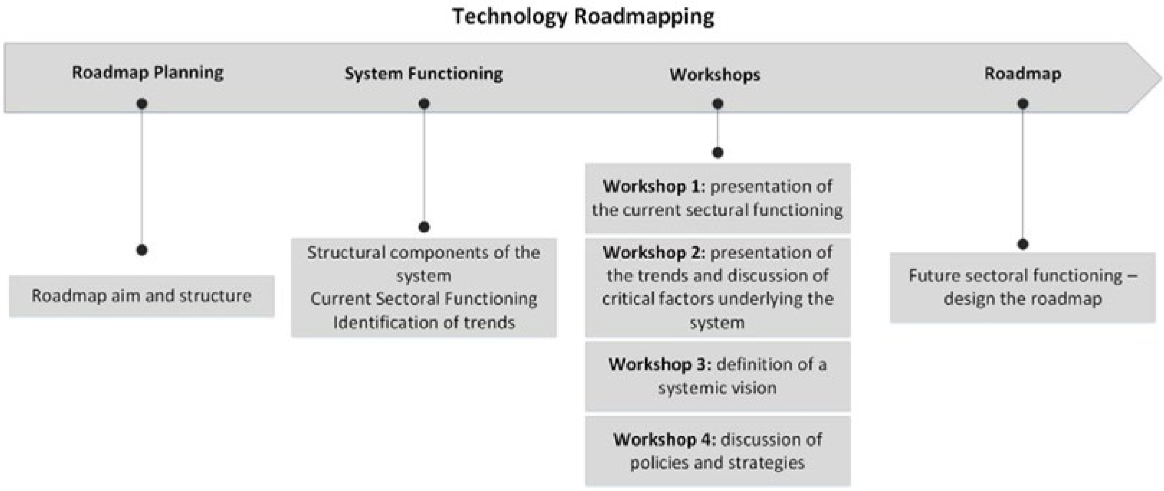

Figure 8 Outline of the roadmapping process (Haddad & Uriona Maldonado, 2017, p. 255)

The resulting TRM considers many different perspectives and as well integrates sustainability as a sub-perspective of the market perspective (see "F5" in Figure 71). Integrating sustainability (or perspectives in general) "manually" in this context means that links and interrelations of artefacts are evaluated non-automated/non-analytical and each by a time by a group of domain experts within several workshops. Thus, with a rising number of assessed perspectives, the complexity (number of possible interrelations of artefacts to be taken into account) of the TRM is growing exponentially as well.

Although this approach requires comparably little previous methodical knowledge and still ensures a highly individualized outcome to the topic of the TRM, the huge labour-intensity due to the necessary large teams of experts to assess the relations of larger TRM must be recognized. Additionally, the traceability of decisions and repeatability of the outcome without the original team might be poor if not forced by exceeding documentation, which again would make this approach more labour-intense.

Among manual approaches, the T-Plan method of Phaal et al. (2004) offers a popular and more standardized process of creating TRM while still using the workshop-approach. Additionally, it can be adapted to include analytical methods as described in the following section.[6]

b) Analytical Integration of Sustainability as a Perspective

As the only source that integrates all perspectives of Q4, the TRM for carsharing technology as well includes product artefacts. The aforementioned rising complexity by number of interrelations of such a highly integrated TRM is handled by an equally high level of analytical methods. By creating quantified causal-loop-diagrams (see Figure 10), Geum, Lee, and Park (2014) not only managed to put very different perspectives into a relation, but also made a multi-scenario evaluation of these perspectives possible (see Figure 9).

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[6] More information about the T-Plan approach is described in “Fast-Start Roadmapping Workshop Approaches” (Moehrle et al. (2013)

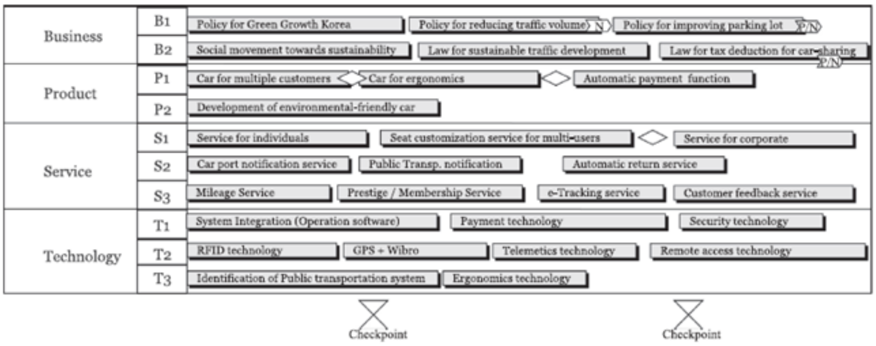

Fig. 5. Technology roadmap for O–A case (optimistic scenario).

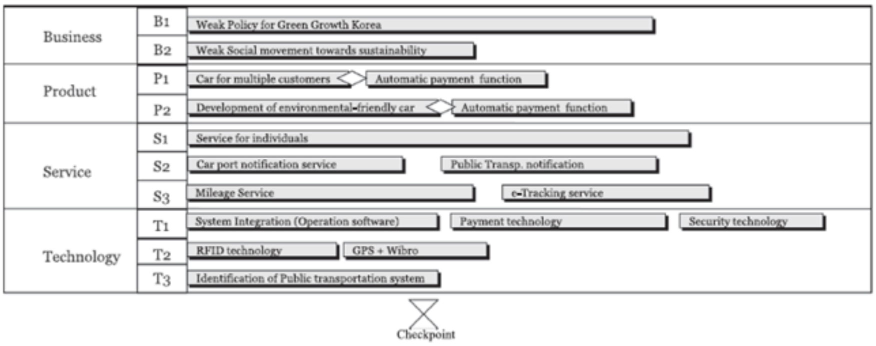

Fig. 6. Technology roadmap for P–A case (pessimistic scenario).

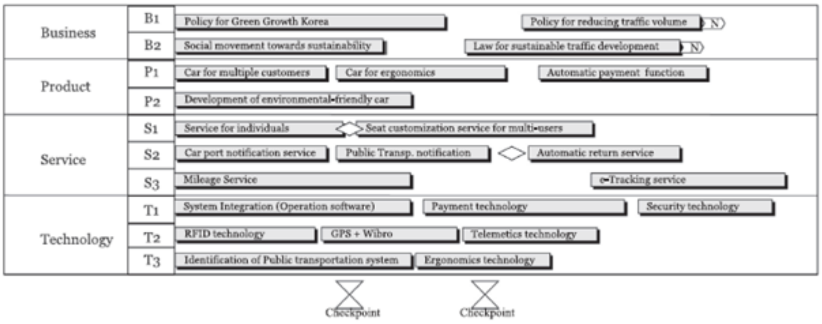

Fig. 7. Technology roadmap for N–A case (neutral scenario).

Figure 9 Multi scenario evaluation of TRM for carsharing (Geum et al., 2014, p. 44)

The three scenarios (optimistic, pessimistic, neutral) are the result of three overarching steps:

- defining factors,
- putting them in dependence (see Figure 10) and
- altering these factors over time (see Figure 11).

The numeric results (see Figure 12) were then analyzed to develop the final TRM.

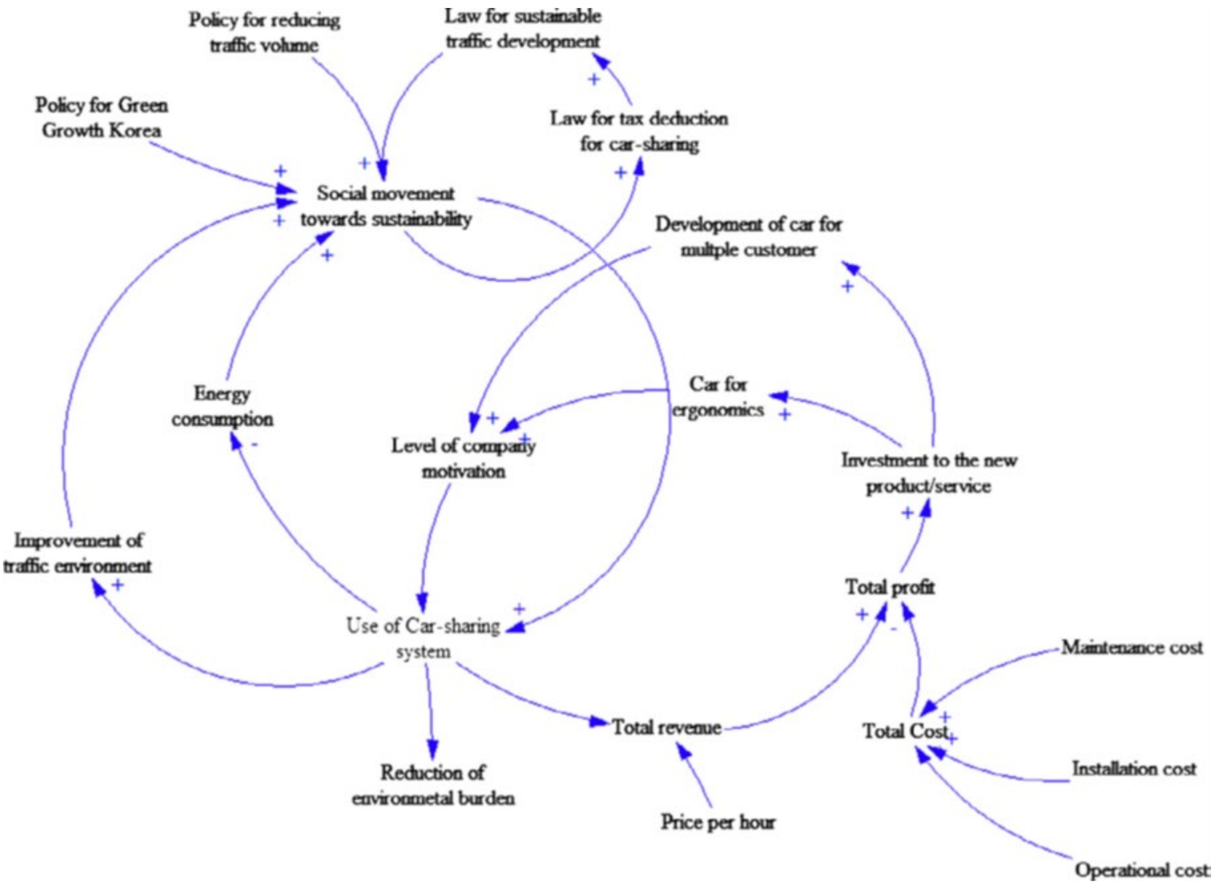

Figure 10 Causal and loop diagram for optimistic scenario (Geum et al., 2014, p. 45)

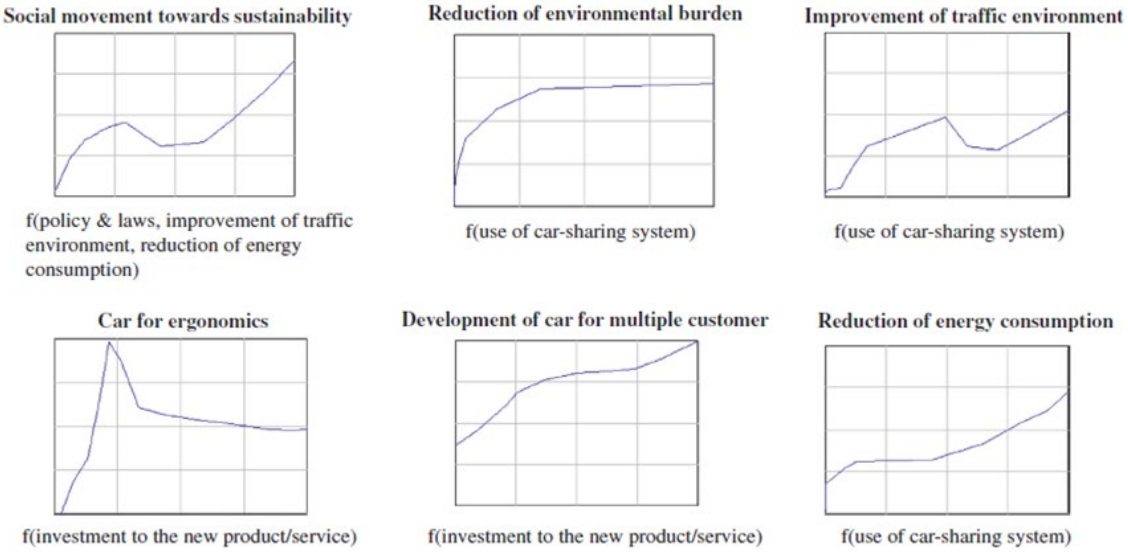

Figure 11 Long term behaviour pattern of input variables (Geum et al., 2014, p. 45)

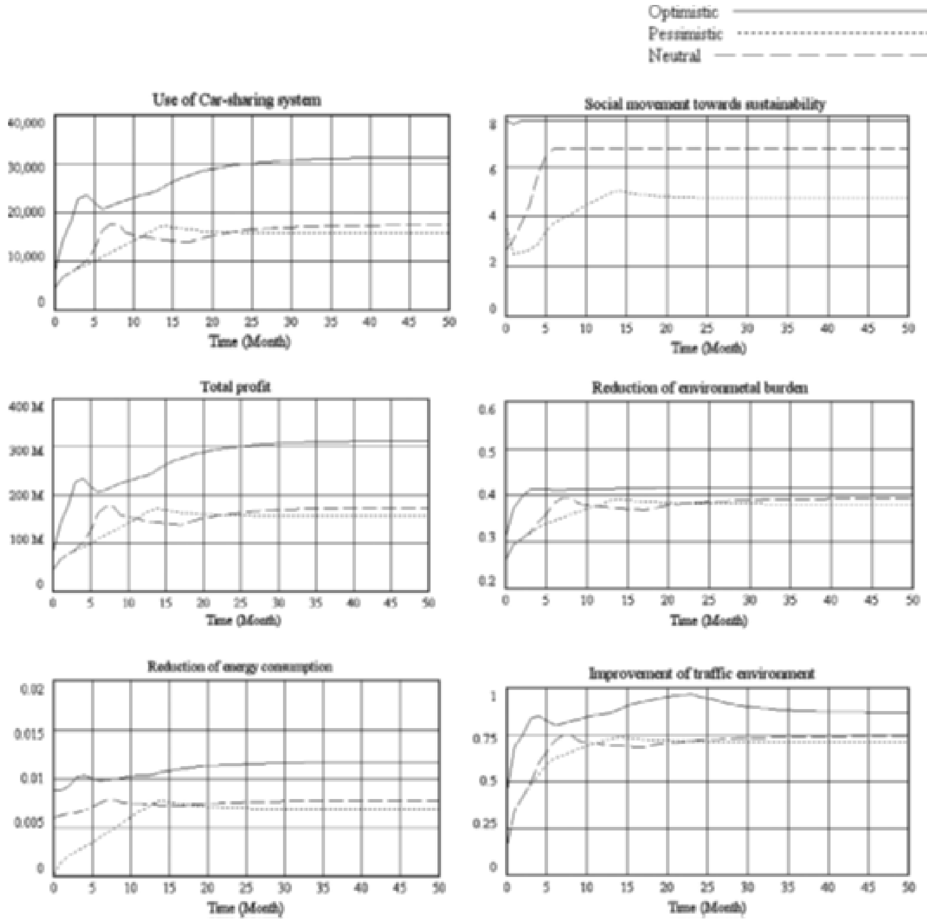

Figure 12 Result of system dynamics simulation (Geum et al., 2014, p. 47)

Another example for an analytic integration method is depicted in Figure 13 by the TRM for "construction R&D through interdisciplinary research efforts". As shown in Figure 14, different research projects are mapped to different goals and among these, to sustainability. However, sustainability is as well an own sub-perspective among others, as seen in Figure 15.

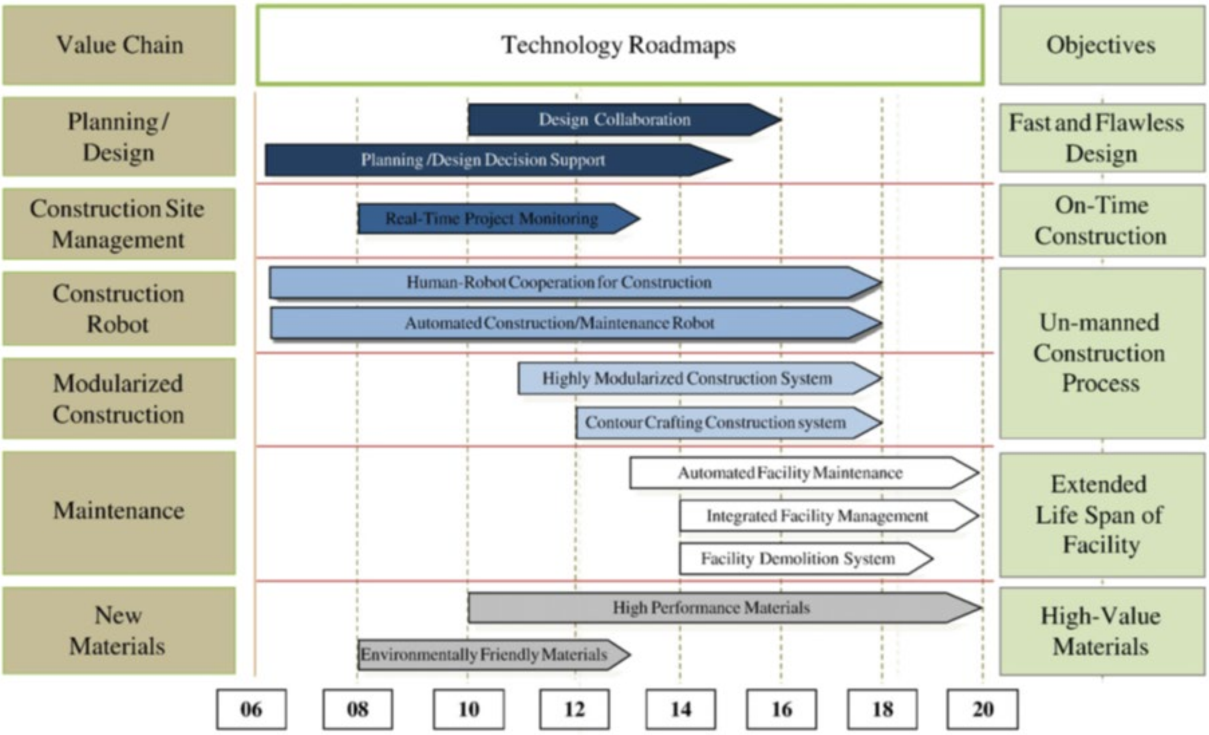

Figure 13 Technology roadmap for construction R&D at a macro level with 12 grouped sub-technology roadmaps (Kim et al., 2009, p. 335)

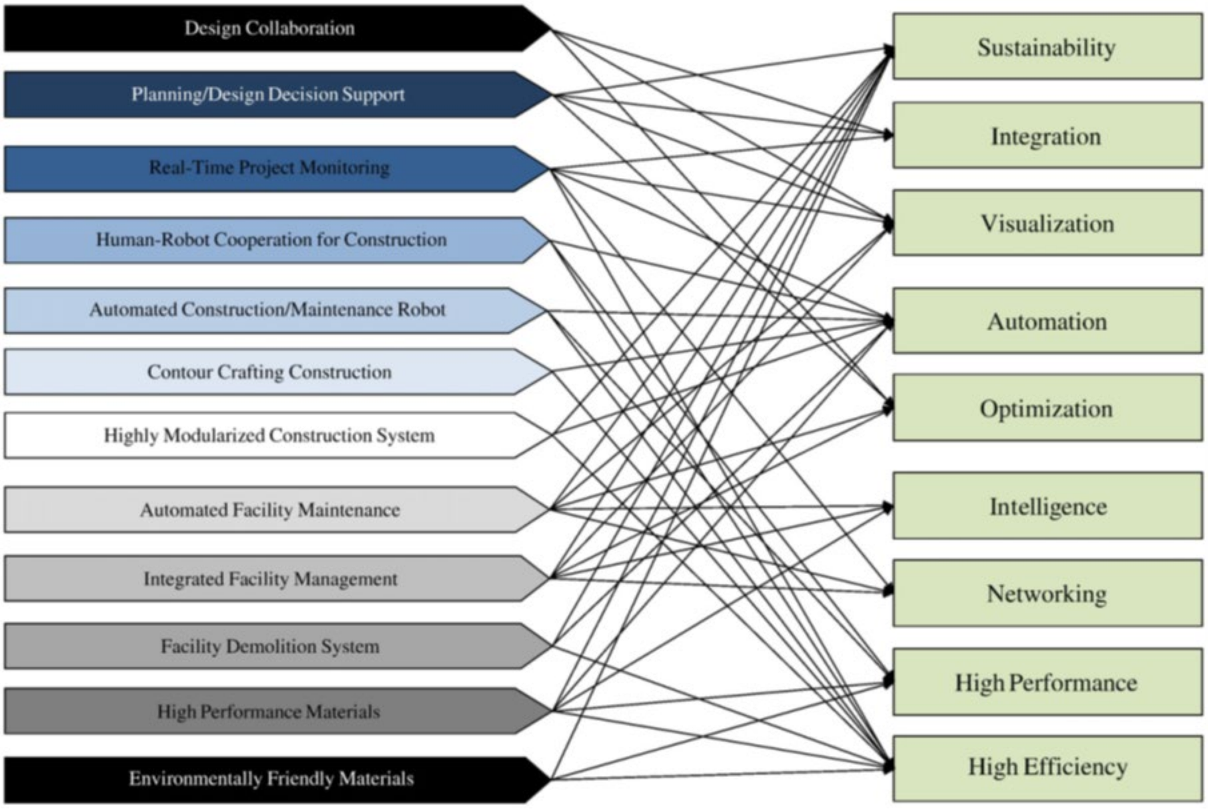

Figure 14 Assignment of sub-technology roadmaps to different research aspects, including sustainability (Kim et al., 2009, p. 336)

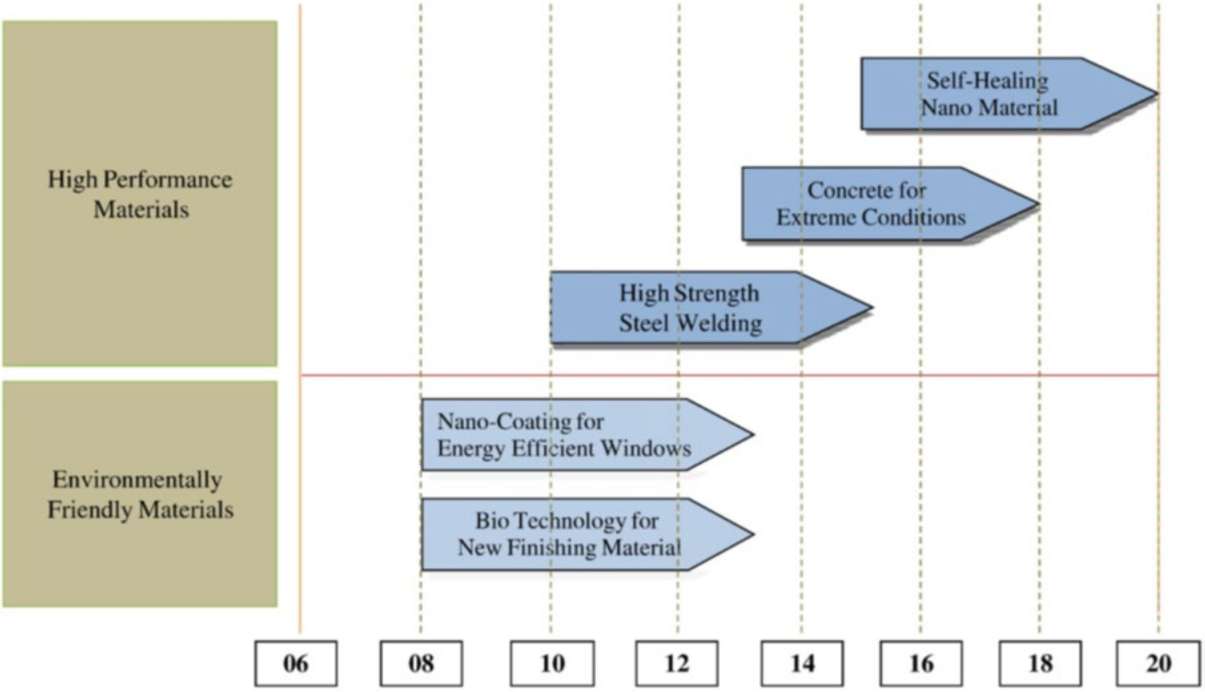

Figure 15 Sub-technology roadmap for new materials in construction with separate perspective for sustainable aspects (Kim et al., 2009, p. 335)

A similarity of these roadmaps is their approach of integrating sustainability as a relevant factor by quantizing all factors and/or interrelations in the TRM. Using different methods like stock and flow diagrams (SFD) for the quantification of artefact-links and the analytical hierarchy process (AHP) for prioritizing the different research projects, both of these TRM evaluated sustainability tantamount to the other perspectives (like technology, regulation or politics).

In comparison to the manual integration method in the previous approach a), an analytical integration approach implies more processual and methodical knowledge. It still requires a lot of manual effort during the process of technology roadmapping and especially extensive front-loading activities by means of choosing and adapting suitable analytical processes. Therefore, it may be way less suited for a fast-start to technology planning than several manual approaches are.

However, once set up, this approach enables much more scalable results in terms of multi-perspective and multi-scenario evaluations at maintainable additional efforts, as interrelations are evaluated in a, to a certain extent, numerical way. Because of these numerical expressions, the interrelations of the final TRM are more comprehensible and the outcome is repeatable with less effort, as the previous front-loading activities can be adapted or even skipped.

c) Automated Integration of Perspectives by Data Mining

While the aforementioned approaches both involved manual evaluation-steps carried out by domain experts within the regular TRM creation process, a third approach was found among the roadmaps of the literature research that further lessened the involvement of those. In

“Technology-driven roadmaps for identifying new product/market opportunities: Use of text mining and quality function deployment”, Jin, Jeong, and Yoon describe a process in which whole TRM for existing or new technologies are created automatically by computational text-mining (see Figure 16).

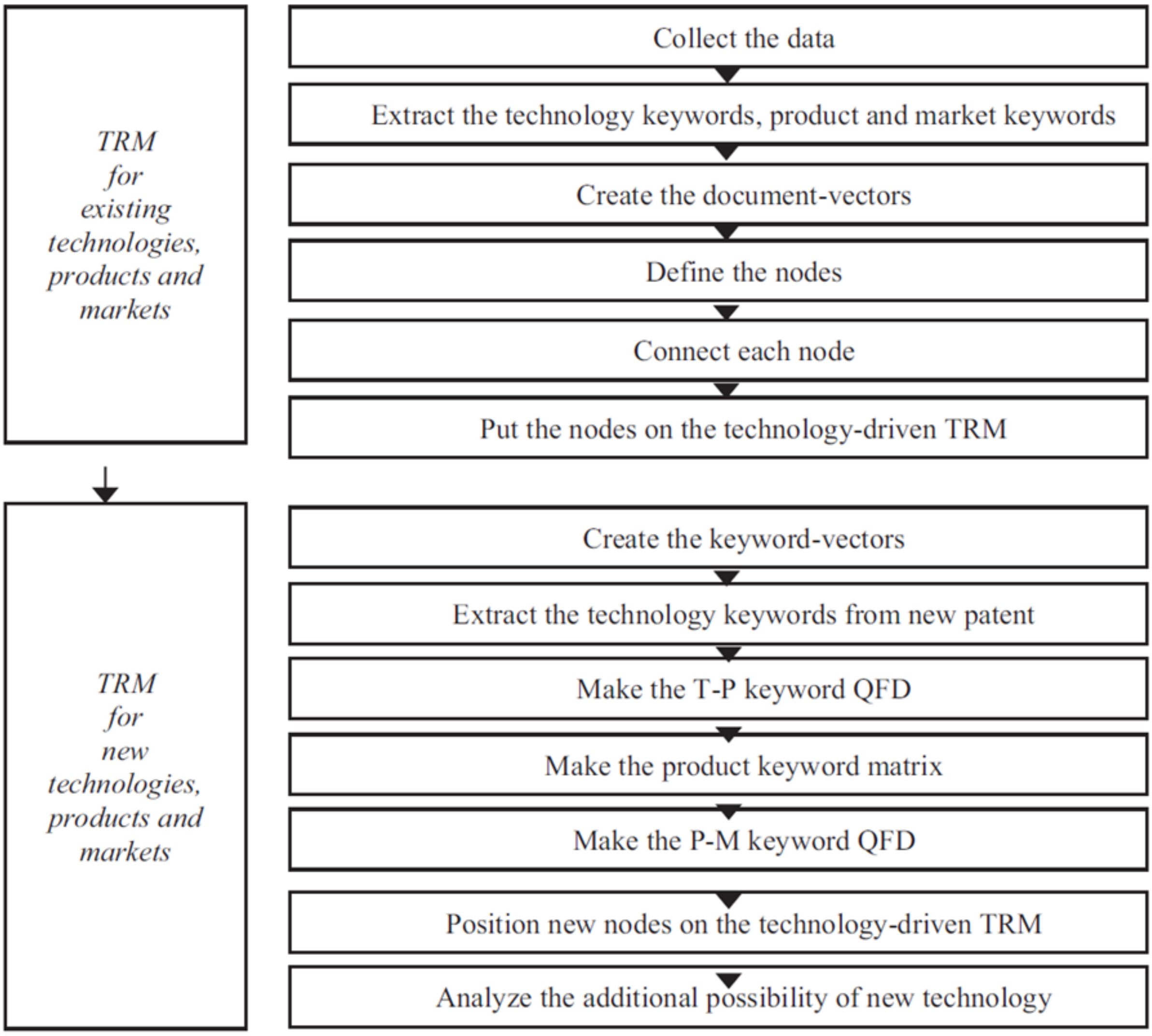

Figure 16 Technology-driven TRM process (Jin et al., 2015, p. 129)

In their approach, TRM were created that consist of

- three perspectives (technology, product, market),
- corresponding artefacts that represent delimitable technologies, products and markets (or delimitable groups of each) and
- connections of these artefacts that represent a certain development direction within one layer or interrelations from one layer to another.

In a first step, the base data is provided by documents of different information and kind (see Figure 17).

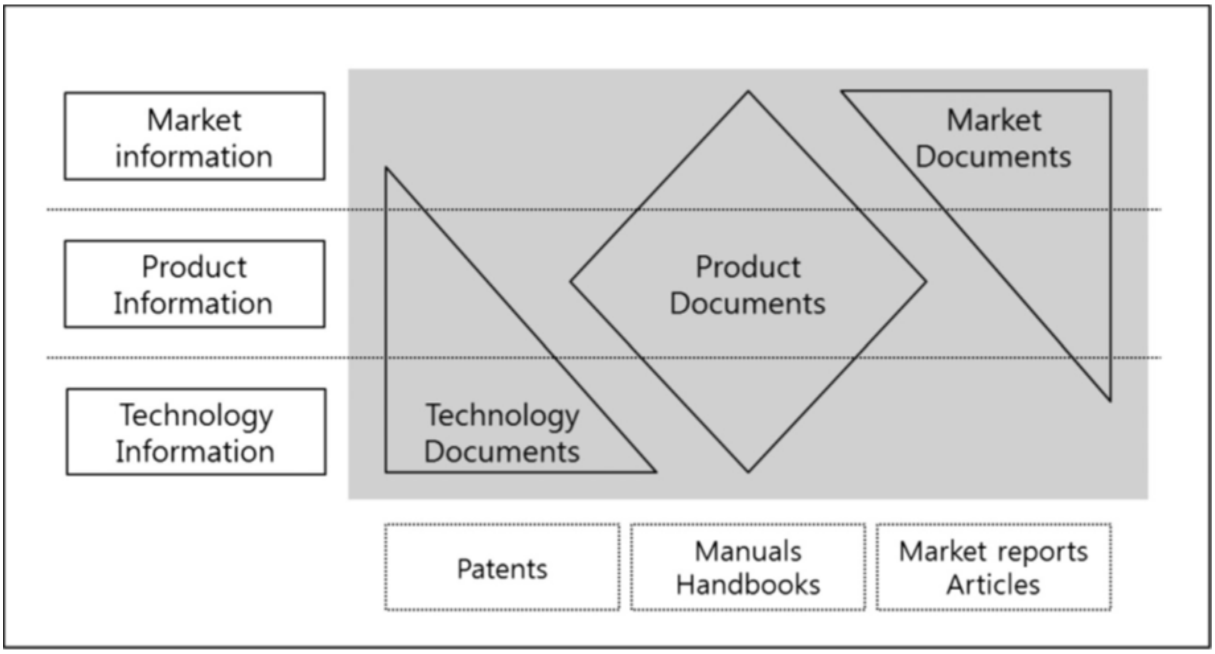

Figure 17 **Relationship among technology, product and market documents (Jin et al., 2015, p. 130)**

With this data, document vectors are created that link single documents to important keywords by counting them. The efficient choice of these keywords still relies on domain-experts though. After setting up these vectors, the definition of similarity is to be carried out by a computational method, like the Euclidean distance, inner product or cosine coefficient. In the given paper of Jin et al., the cosine coefficient is used for two purposes. Firstly, very similar technologies are grouped together to form a single artefact. Secondly, interrelations and subsequent developments are based on computed similarity among documents and depicted as connectors. While the relation of existing technology of the three layers is included in the base-data, this relation has first to be evaluated for new technology (see Figure 16).

This is done by two quality function deployments (QFD), with the adjustment that the score for the relationship degree of certain technologies is again calculated by similarity, rather than evaluated by experts. Ultimately, the resulting artefacts and connectors are applied to a time-depended TRM by either using the exact time described in the documents, for example the launch date of products, or by using average times for new technology (Jin et al., 2015, pp. 128–134).

As a result, two TRM are presented: one for existing technology (see Figure 18) and one for new technology (see Figure 68). Jin et al. as well validated the result by comparing it to a roadmap drawn by domain experts in an analytical way and received relatively high accuracy and low error rates with 80.64% and 19.35%, respectively (Jin et al., 2015, p. 135).

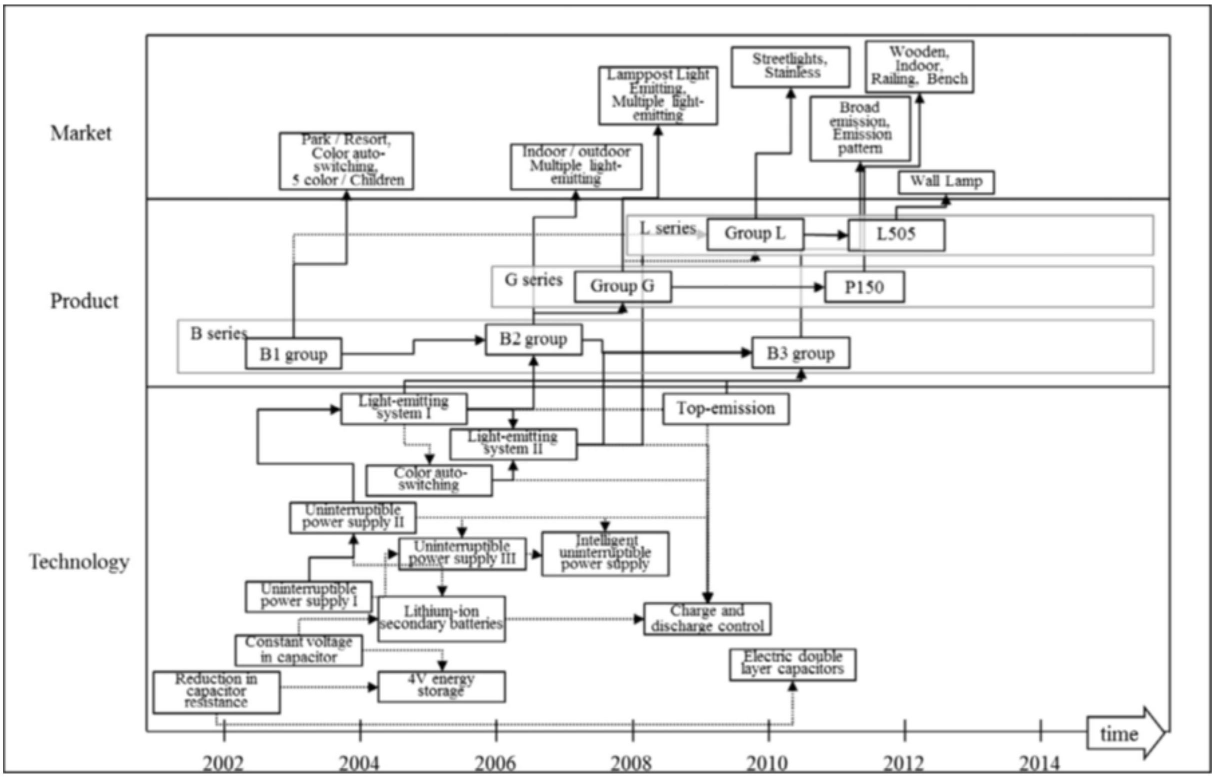

Figure 18 Technology-driven TRM for existing technology (Jin et al., 2015, p. 134)

In conclusion, the presented approach showed the highest rate of automatization among the found roadmaps while still maintaining a good accuracy. Domain experts are only involved at a single step (definition of important keywords), which moreover belongs to the frontloading activities that do not have to be repeated at later repetitions of the TRM-creation process.[7] Thus, extensibility by either means of more data-sources, more perspectives or other target-domains is given without exponentially growing effort which separates this kind of approach in comparison to the ones identified in sections a) and b).

At this point, it must be noted that the role of sustainability in this specific TRM is rated as a side effect only (see Q1a, section Q1). However, in evaluation of the general approach, this specific circumstance may be compensated by the aforementioned extensibility.

Another characteristic of this method is that it not only requires a high degree of methodical knowledge in terms of analytical methods, but as well necessitates a high degree of knowledge about text-mining and automated data-extraction, which is not needed for the other approaches. The frontloading activities and necessary analytical adaption is to be considered even more extensive than in section b), as not only the kind of relations are numerically described (*How are two artefacts related to each other?*), but as well their occurrence (*Is there a relation between two given artefacts?*) and the occurrence and kind of artefacts itself (*Is a*

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[7] This is limited by the change of importance of certain keywords however, which again makes repetition of this step necessary.

given described technology or group of technologies a delimitable artefact in the general development of the examined technology-path?)

d) Comparison of Approaches

In the sections before it was shown, that integrating sustainability into TRM can be handled at different levels of human domain expert interaction or, in other words, by a differing degree of automation. This estimation is depicted in Table 5 and further explained below.

Table 5 Comparison of integration approaches

Degree of Automation	**Manual Integration**	**Analytical Integration**	**Automated Integration**
Necessary Methodical Knowledge	Medium	Medium	High
Necessary Analytical Knowledge	Low	High	Very High (Data-Mining)
Frontloading Activities for the first TRM	Medium	High	Very High
Frontloading Activities for subsequent TRM		Medium	Low
Necessary Work for the first TRM	(Very) High	Medium	Medium
Necessary Work for subsequent TRM			(Very) Low
Increase of Work for multiple Perspectives	(Strongly) Exponential	Exponential	Linear

Generally speaking, all of the approaches require basic knowledge in terms of methods to carry out the TRM creation process by the person(s) who will lead the TRM project. However, additional methodical and analytical skills to set up formulas and to code data-mining programs are necessary to further automate the process.

As the manual integration by numerous workshops with domain experts is highly dependent on human interaction, existing domain knowledge and discussion, it is quick to start with comparably little frontloading activities, beside workshop preparation. In this context, frontloading activities describe necessary methodological steps that are not related to the topic of the TRM at all, but have to be done in preparation before starting to work on the actual topic of the TRM. In comparison to the manual integration approach, the analytical and automated approaches require partially labor-intense preparational steps for setting up numerical relations, formulas, factors and programs which require both methodical and analytical knowledge.

These steps pay off at later repetitions of the TRM creation process however, as analytical prerequisites do not change at all or need very little adaption over the time. At this point, the effort for frontloading activities of manual integration approaches remains the same, beside productivity increase of repeating the same steps again.

The most important difference comes with the increase of work in relation to an increasing number of examined perspectives. The complexity for each additional perspective is rising because it needs to be set in relation to the existing ones and vice versa will exert influence on the existing perspectives. This reciprocal effect is extenuated by analytical formulas which numerically describe the connections of artefacts (*how* artefacts affect each other), but still leaving artefact choice, placement, and connection (*which* artefacts affect each other) to domain experts.

If, for example, a certain law is going to be enacted at a later year, the impact on all directly and indirectly connected artefacts have to be re-evaluated. This might end up in having huge impacts on technological succession and market penetration.

In contrast to the aforementioned approaches, the fully automated approach shifts this re-evaluation steps to computational algorithms running on a processor. Given the processing capacity of today's CPU's and the possibilities to split multi-threaded processing-load to GPU's, the rise of TRM-complexity due to new perspectives or adjustments will only have a linear impact on the TRM-creation time.

Generally speaking of integration approaches for new perspectives in TRM, there is a shift of work going from a manual approach to an automated one: While frontloading activities heavily increase, the work for the first and subsequentially TRM drops. It is to be evaluated by the project team, if the TRM should be a scalable long-term technology planning framework for the company, which therefore justifies the frontloading effort of building up knowledge and the necessary IT backbone, or if it should be more individualized snapshot and reflecting the current state of expert domain knowledge, which requires more manual effort by a larger project team.

However, specifically regarding the integration of sustainability in technology roadmapping, the complexity of the process is likely rising in an exponential way. This might be reasoned by the versatile and often conflictive ways in which sustainable aspects have influences on today's heavily economic-focused business processes. The little share of TRM that actually included sustainability as a perspective in the content-oriented classification supports this statement (see Table 4).

It is now to be evaluated, if modern IT tools are able to facilitate the implementation of sustainability, how they might solve general problems of technology roadmapping and which IT concepts might ultimately help to even overcome traditional barriers[8] of integrating it as a planning tool.

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[8] Traditional barriers are further explained in section 3.1.2.

3 IT based Framework facilitating Technology Roadmapping striving for Sustainability

To give answers to the questions *if* and *how* current IT tools are able to facilitate the implementation of sustainability in technology roadmapping, another question is put in front first: how are those tools able to facilitate each technology roadmapping and sustainable development in general?

While systematically examining different examples and approaches of software tools, special attention is given to external application interfaces (API's). These are necessary to establish a connection automation between tools for technology roadmapping and sustainable development and ultimately can lead to an integrated approach of both. While in sections 3.1 and 3.2 the use and extend of preassigned API's is described in general, the utilization of these regarding the interplay of technology roadmapping and sustainable development planning is explained within an IT architecture concept in section 3.3 and reviewed in section 3.4.

3.1 Synopsis of Software Tools supporting Technology Roadmapping

As comprehensively explained in previous sections, the complexity of multi-perspective TRM is extensively rising due to growing versatility of product requirements. In section 2.2, the effect of integrating highly complex sustainable aspects into TRM was examined and, depending on the degree of automation, showed a significant impact on the technology roadmapping process regarding the frontloading activities, execution effort and effort for later repetition.

As complexity handling is a central issue of technology roadmapping in general, a variety of software tools were created to facilitate technology roadmapping over the years. To systematically describe the facilitation potential of these IT solutions, an abstract classification logic is explained first.

3.1.1 Classification of Software Tools supporting Technology Roadmapping

While there are many ways to classify software tools, a suitable two-dimensional superordinate classification for TRM-software was found in the description of Isenmann (2008) and depicted in Figure 19.

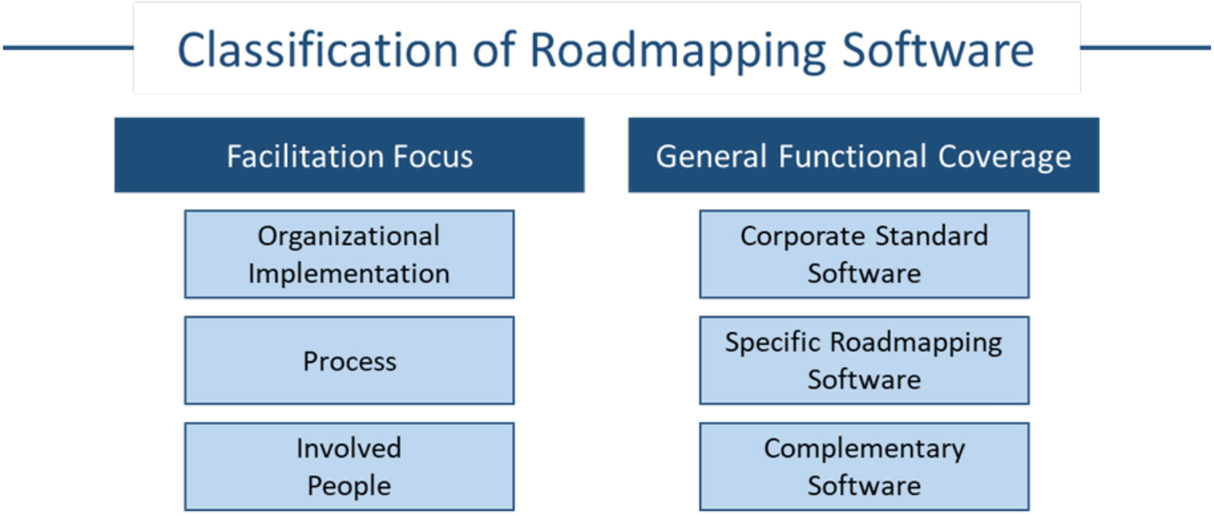

Figure 19 Classification of software tools supporting technology roadmapping according to Isenmann (2008)

Facilitation Focus

Generally, software tools may be used to facilitate internal processes and the organizational implementation of such. As shown in previous sections, improved information management, communication and cooperation of different departments is essential to handle the complexity of multi-perspective roadmaps. Therefore, the analysis of the facilitation potential will include the following three aspects: (Isenmann, 2008, pp. 230–238)

- *Organizational Implementation:* How is the software tool to be implemented in the organization and how is this implementation facilitated by suitable IT methods?

  While first roadmapping tools were able to be introduced to corporate technology planning in a more or less greenfield approach, nowadays corporate IT landscapes are already covered with software tools, databases and systems. To gain competitional advantage over other tools, quicker and less extensive implementation phases and long-term usage within the company, tools for technology roadmapping need to have measures defined to be implemented into an existing IT and process landscape of any company.

- *Process:* Which processual steps of technology roadmapping are facilitated to what extend? How is a successful digitalized implementation into existing, under circumstances manual, processes ensured?

  A continuous digital workflow of the core processes of technology roadmapping (creation, visualization, maintenance, archival storage, evaluation, processing) is needed to exploit the full facilitation potential of software tools. The implications of this statement will be further examined in section 3.1.3.

- *Involved People:* Which methods and tools are included to facilitate the necessary cooperation of TRM creators and process participants?

  The application of software tools can as well fundamentally change the modus operandi for technology roadmapping, which formerly included a likely sequential creation process, synchronous cooperation and editing of TRM in workshops and a mere confidential handling of information as business secrets.

For a successful implementation, all three aspects have to be dealt with at the same time, as each will have an influence of the other. Because of this, the evaluation of the software tools will focus on distinctive features of the tools that facilitate assignable aspects. These are then partially translated into IT concepts to facilitate the integration of sustainable aspects into technology roadmapping in section 3.3.

General Functional Coverage

In Order to differentiate holistic tools for strategic planning from those that focus on a single aspect of technology roadmapping, a distinction regarding the functional coverage is made: (Isenmann, 2008, pp. 240–241)

- *Corporate Standard Software:* Holistic tools or IT Systems for strategic planning that facilitate processes beyond technology roadmapping.
- *Specific Roadmapping Software:* Tools that focus solely on the core processes of roadmapping.
- *Complementary Software:* Tools that focus on single process-steps or selective accompanying processes.

3.1.2 General IT based Issues concerning Technology Roadmapping

While the aforementioned facilitation potential and functional coverage are bound to the topic of software for technology roadmapping, there are certain general issues of digitalization that play an important role specifically for technology roadmapping as well. These issues are now briefly categorized in *success factors* and *barriers to success* with each corresponding facilitation potentials of a continuous digitalized workflow.

a) Success Factors

In a survey of 2000 manufacturing firms in the United Kingdom, the four most important success factors of technology roadmapping were named: (see Figure 20, Phaal & Farrukh, 2000, p. 15)

- Clear business need
- Right people / functions involved
- Commitment from senior management
- Desire to develop effective business processes

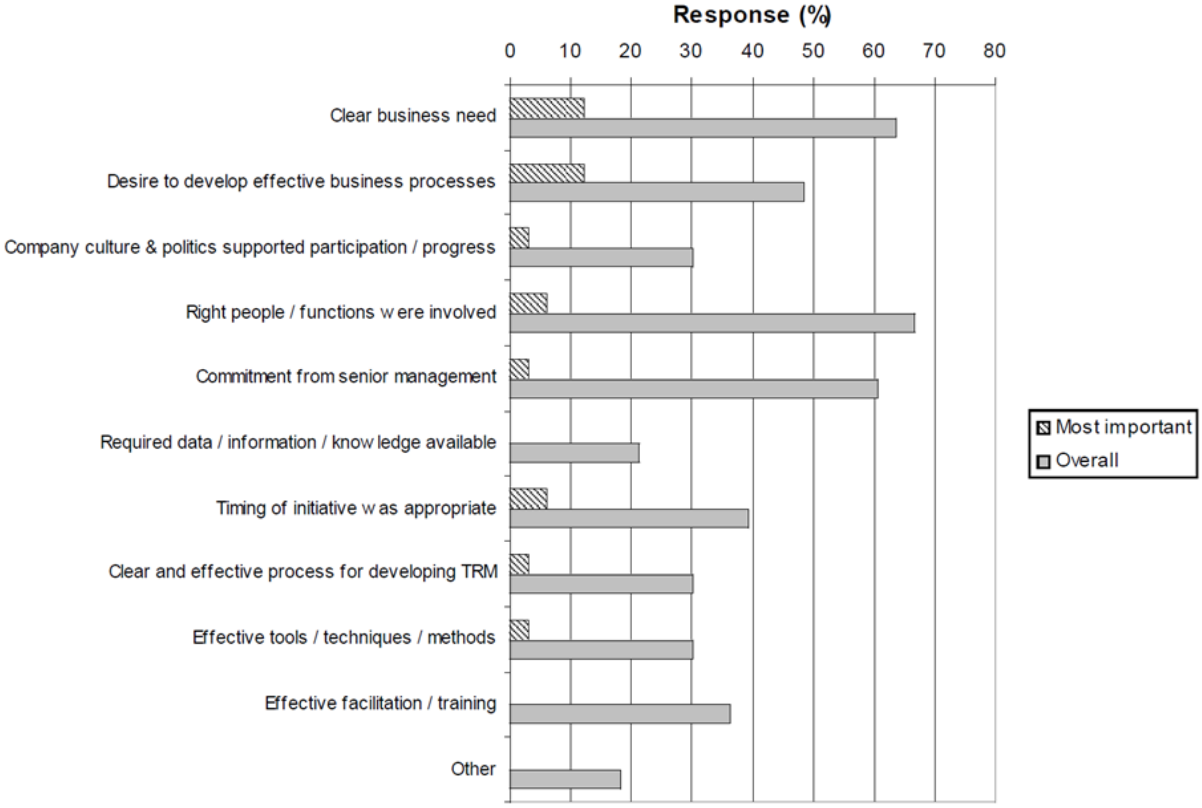

Figure 20 Success factors for technology roadmapping (Phaal & Farrukh, 2000, p. 15)

These correspond well to certain facilitation potentials or focuses of a digital workflow for technology roadmapping: (Isenmann, 2008, p. 235)

- *Cooperation*: IT tools enable an asynchronous inter-departmental cooperation. In other words, different people of different departments may work on the same TRM or database at different times. Because of the automated logging of changes, the traceability of TRM is improved and decisions becoming transparent. This, together with the TRM being the result of collective effort, helps to prevent so called silo-mentality and cases of the “not invented here”-syndrome.

- *Communication*: As for cooperation, even communication is altered into an asynchronous form by means of comment- and task-management-features of IT tools. Together, these two facilitation potentials help to get the right people or functions involved in the process in an efficient way.
- *Strategic profiling*: TRM help to visualize complex interrelations and dependencies, which can help the management to formulate reasoned decisions and align the company according to a complex market situation. While doing this, additional competitional advantages can be taken by using this information for marketing purposes at product-launches.
- *Focus on processes and organizational implementation* (see section 3.1.1)

Barriers to Success

In the same study as mentioned in a), the four most important barriers that prevented the success of technology roadmapping in companies were the following: (see Figure 21, Phaal & Farrukh, 2000, p. 15)

- Initiative Overload / distraction from short term tasks
- Required data / information / knowledge not available
- Lack of clear and effective process for developing map
- Lack of effective tools / techniques / methods

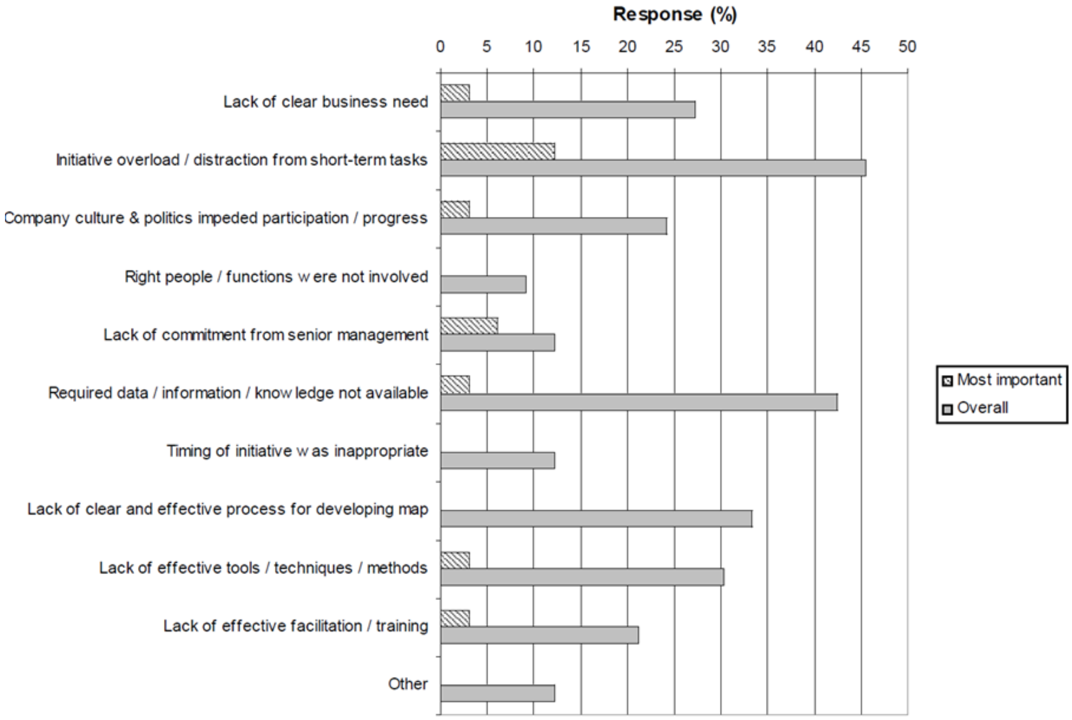

Figure 21 Barriers to success for technology roadmapping (Phaal & Farrukh, 2000, p. 15)

These factors are complemented and acknowledged by general mistakes for technology roadmapping: (Isenmann, 2008, pp. 262–263)

- *Isolation*: the composition of the roadmapping team is too homogenous
- *Obsolete information*: the base information/data for planning is overaged and not updated frequently
- *Intransigence*: compromises cannot be found due to an unwillingness of the participants
- *Disregard*: decisions are taken by favouriting single roadmaps rather than by a holistically derivation taking all roadmaps into account
- *Determination*: The specific outcome in form of a roadmap is already imagined by the participants and forced to be created rather than taking advantages out of the interdepartmental process of technology roadmapping
- *Missing conjunctions*: Single intra-roadmap developments are not connected to other roadmap developments for an integrated technology roadmap.
- *Short-termism*: the planning horizon is too narrow to examine long-term correlations of developing markets and technologies.

The avoidance of these barriers and mistakes can be accompanied by facilitation aspects of a digital workflow: (Isenmann, 2008, p. 235)

- *Information-, process- and tool-standardization*: To digitalize a complete workflow, information and interfaces between tools or databases must be standardized or at least explicitly defined. Deviations from this, like workarounds and manually coded fixed interfaces, quickly increase the maintenance effort and prevent further scaling and connection to complementary workflows or information systems.
- *Efficient information management*: With the standardization in mind, efficient information management becomes feasible in terms of possible digital information distribution, comparison, actualisation and correction. Therefore, internal collaboration on the same database leads to an up-to-date and holistic planning basis. Furthermore, accessibility can be digitally controlled and thus enhanced beyond the corporate scope. A finely graduated information sharing and cooperation with external colleagues and companies is enabled at the same time, as the risk of sharing business secrets is minimalized.

The aforementioned factors and barriers to success are put into relation and depicted in Figure 22, together with related facilitation potentials of a digitalized workflow.

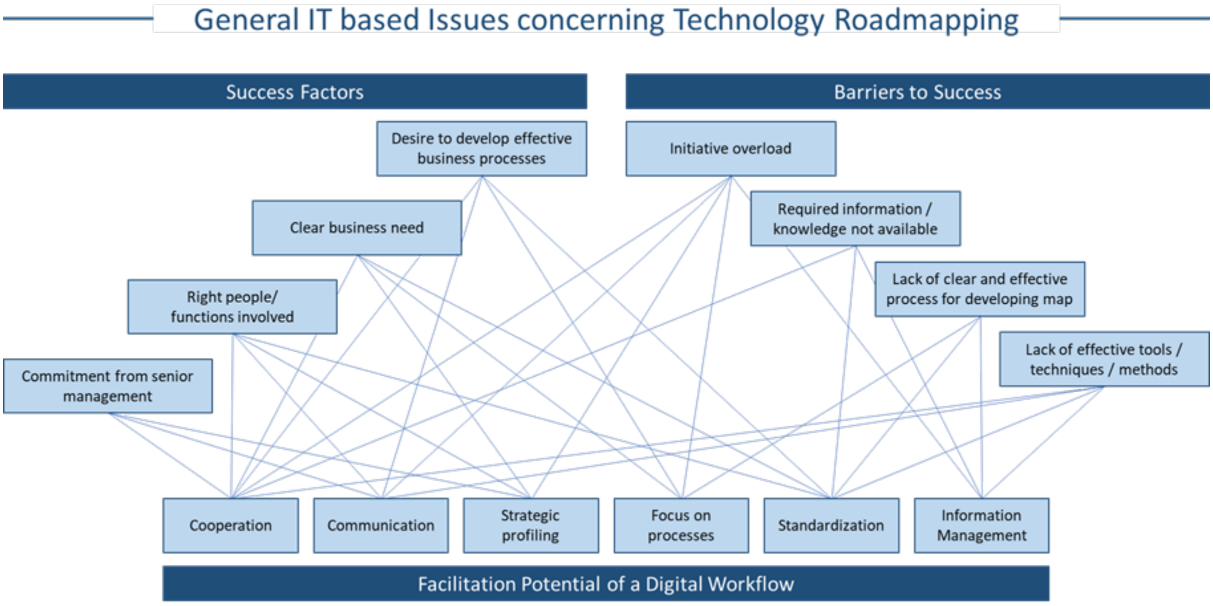

Figure 22 Conceptional illustrated relationships of IT based issues concerning technology roadmapping based on Phaal and Farrukh (2000) and Isenmann (2008)

It becomes evident that a seamless workflow-digitalization (see bottom of Figure 22) may help to implement technology roadmapping as a holistic long-term planning method as it facilitates the most important success factors and helps to overcome barriers respectively. However, to exploit the facilitation potential, complex relations within the corporate environment that alter from one company to another have to be considered.

Therefore, IT applications and a digitalized workflow are strictly not to be handled as a panacea for technology roadmapping in particular or for the improvement of business processes in general, but rather as supportive tools and methods to necessary conversions and the foundation to innovate internal approaches and processes.

3.1.3 Selective Examples of existing Software Tools for Technology Roadmapping

As aforementioned, nowadays business processes are increasingly assisted by software or even completely mapped into multiple applications or single systems. Because of the wide range of software tools for enterprise resource planning (ERP), innovation- and project-management, only selective examples are introduced in this section. In Figure 23, the chosen examples are arranged by their functional coverage and additionally evaluated by their facilitation focus.

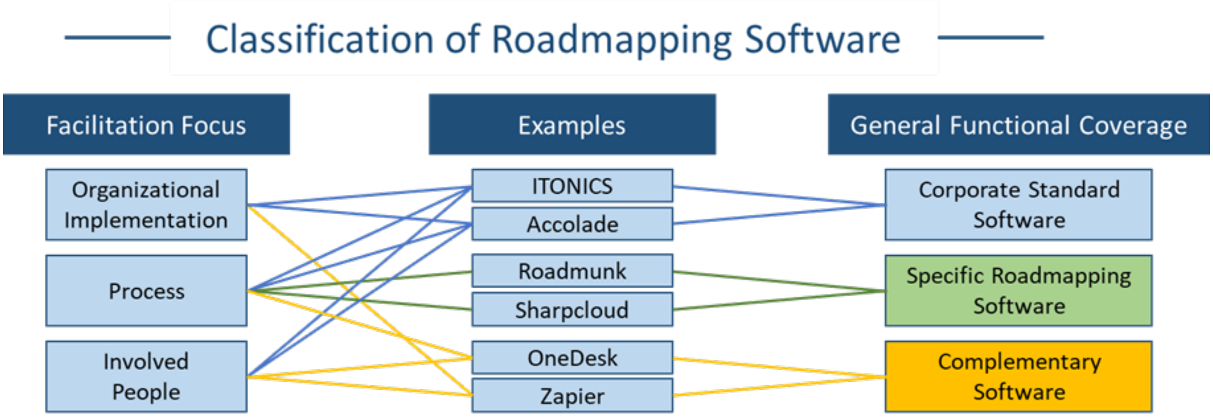

Figure 23 Synopsis of software tools supporting technology roadmapping (based on Isenmann, 2008)

a) Corporate standard software: ITONICS Enterprise by ITONICS GmbH as an example for an end-to-end innovation management tool

The first example of a corporate standard software is given by the IT System of ITONICS GmbH. Referring to Figure 24, the holistic idea of the innovation management system is about to solve the most common tasks and topics along the innovation process with separated tools from the same software supplier and conjoin them in a single system.

In this example, ITONICS GmbH created several modules that are each represented by a circular symbol in Figure 24. With the modules *ITONICS Foresight, Scout* and *Technology Radar*, the input information for technology roadmapping can be searched, composed and integrated without leaving the environment of the IT system. Especially the combination of automated text-mining from over millions of web-sources and patent databases and further processing in technology clusters or future scenario evaluations is greatly facilitating the information management of the users. As all information is saved within the system and accessible via a simple web-interface, the creation and further development of technology roadmaps is realized user-friendly and is scalable from a single user to whole teams. Changes and contributions of several team members can be are tracked automatically and called for, for example when there is need for expert knowledge input. The facilitation potential of the tool regarding the involvement of people and teams is additionally given by a self-explanatory HMI and cooperation methods like comments and automated mail-alerts that support asynchronous work on the TRM (ITONICS GmbH, 2020a).

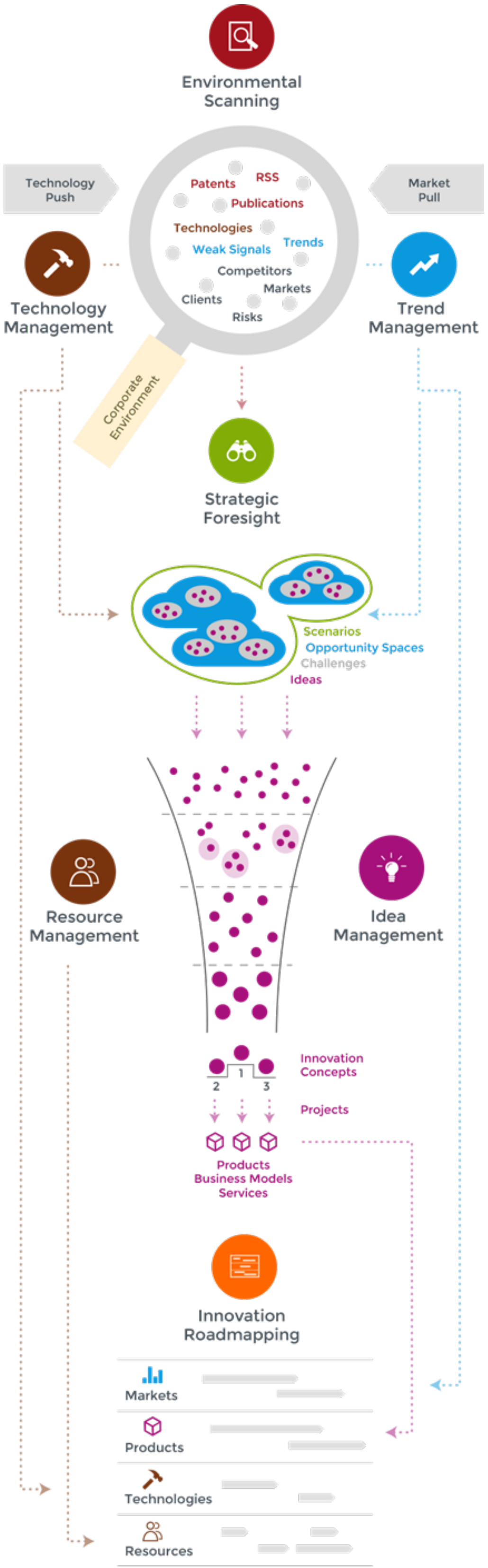

Figure 24 Functional coverage of ITONICS enterprise (ITONICS GmbH, 2020a)

Given the holistic approach of the tool with a seamless digitalization along the process of technology roadmapping, the process facilitation potential is rather all-encompassing than focused on a single step. However, this is limited to the usage of the full range of ITONICS' IT products in a greenfield approach to technology roadmapping.

Given an already existing process with manual steps and "traditional" workshops, the full exploitation of the facilitation potential hypothesizes a relocation of these processual steps into the ITONICS software environment. Otherwise, a manual transmission or a specific solution for an automated transmission of the information into the ITONICS environment is needed. This is not immediately to be equated as a disadvantage, as there are several API's for automated data-import and user-friendly solutions for manual data registration, but a fact to be kept in mind when considering the usage of the software in a brownfield approach. Subsequently, the facilitation potential regarding the organizational implementation is dependent on the positioning of the software within the existing corporate IT landscape.

If the system is used as the main hub for all information and processes regarding technology roadmapping, the ITONICS software is offering a wide range of API's and functionality to facilitate the organizational implementation by importing and integrating existing information. This includes application connectors to Microsoft SharePoint, IBM Connections, JIVE as well as data interfaces via RSS, ATOM, JSON and XML by using RESTful-API's (ITONICS GmbH, 2020c).

If, however, the tool is not used as the central data-sink, but rather in a complementary way with existing tools and bidirectionally connected to existing data-bases, the facilitation potential is considerably less exploited due to less simplified and assisted outbound API's than there are user-friendly inbound API's.

Summarizing, as an example for holistic IT systems, ITONICS enterprise is comprehensively facilitating all aforementioned steps of technology roadmapping and provides a wide range of inbound API's. While the full potential of the tool can only be exploited with a single-system-workflow, discontinuities with tools of other companies may lower the facilitation potential respectively. Therefore, the decision to use this kind of holistic software systems is not only accompanied by a strategic dependency on a single software supplier and its decisions, but also on the corresponding pricing of the tool and continuing maintenance costs. These may, as a part of the software-as-a-service strategy, change over time.[9] (ITONICS GmbH, 2020b)

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[9] The aftermath of this profound dependency of single-source holistic software systems may also be shown by the products of one of the best-known ERP software corporations and its customers: SAP SE (SAP SE, 2020)

b) Corporate standard software: Accolade® by Sopheon as an example for flexible implementation with open application interfaces

As a second example for corporate standard software, Accolade® by Sopheon covers a wide range of tasks for innovation planning and includes a sub-module for roadmapping as well (see Figure 25). This encompasses process steps for roadmap creation, automated visualization, archival storage, maintenance and further processing as well as the involvement of different people and teams. In order to not repeat the aforementioned general co-operational features, dis-/advantages and interrelations of holistic single-source systems, only the peculiarities of Accolade® regarding the positioning of the tool within the corporate IT landscape are highlighted.

Figure 25 Functional coverage of Sopheon Accolade® (SOPHEON, 2020a)

Contrary to ITONICS and its data-centric approach, Accolade® offers the possibility to choose the information standardization and integration approach freely. The decision to do this is reasoned by Sopheons' customer experience and varying degrees of extensive IT landscapes they came upon. To further emphasize the extent to which Sopheon refined this approach, the possibilities of information exchange are specified below and sorted by means of increasing automation: (SOPHEON, 2020b)

- **Manual integration (bi-directional):** For the sake of completeness, the manual registration and reading of data by human interaction is mentioned at this point.
- **Project Importer and Exporter (bi-directional)**: In this mode of operation, Accolade® observes certain configured network locations or FTP-servers supervised or unsupervised[10] and fetches data into reference tables automatically. In the same way, it can automatically write data to certain configured locations (see Figure 26). As a special

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[10] By supervision in this context, the degree of necessary human interaction with the application is expressed. While automated workflows might still need human interaction to be started and are therefore still considered supervised, unsupervised workflows execute themselves under certain automatically observed circumstances like change-events or timed-tasks, run and stop without any needed human interaction.

case of this preassigned Accolade® API, there is a bi-directional Microsoft® Office Integration to automatically im- and export information as commonly used Microsoft® Excel sheets or Comma-Separated-Value (*.csv) files, that are commonly found as export file options for third-party applications.

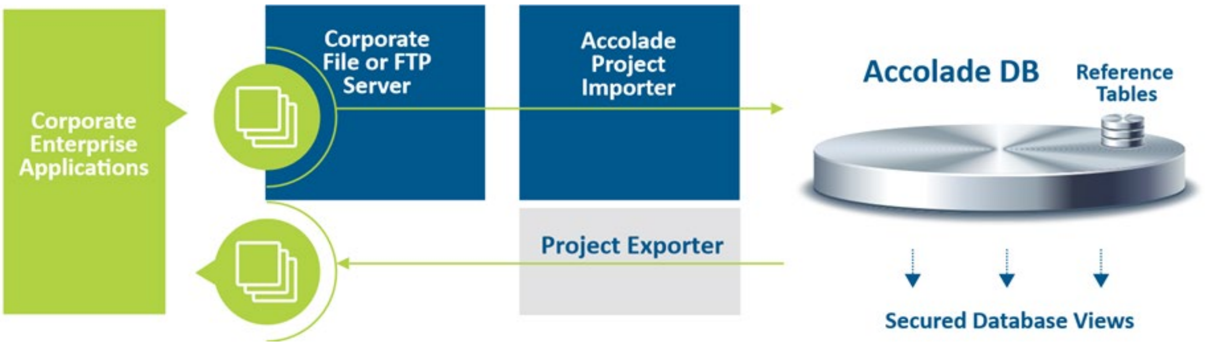

Figure 26 **Functionality of Accolade® project importer and exporter (SOPHEON, 2020b)**

- **API-based integration (bi-directional)**: While this form of data integration is the most advanced regarding possible automation, it also is the most complex as information is directly exchanged through API's without an intermediary exchange file (for example a *.csv file). Accolade® provides a set of web services (like SOAP and RESTful HTTP) which can be used either in enterprise application integration (EAI) middleware for further data-abstraction and -transformation or in third-party applications (see Figure 27).

  At this point, Accolade® can serve both as the central information database that synchronizes peripheric applications (e.g. "pushes" information into other systems), but also as a peripheric database that reacts on external commands of the central database. This is realized by so called linking identifiers that establish a logical relationship between third-party data objects and internal ones, as well as an extensive API that enables external control of Accolade® and vice versa enables Accolade® to control external applications.

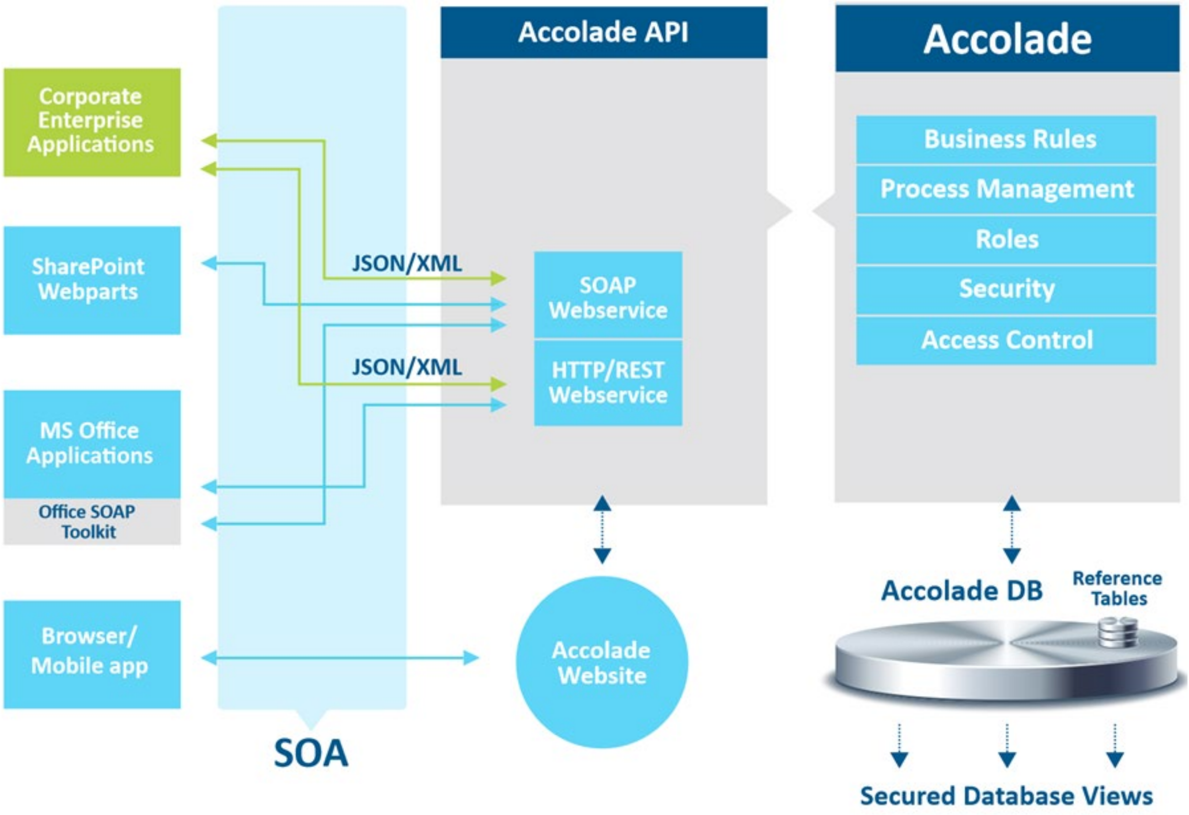

Figure 27 The Accolade® API integration (SOPHEON, 2020b)

- Additional interfaces: There are interfaces for embedded applications that can be integrated into the Accolade® user interface, custom plugins and secure database views that allow Accolade® to transmit particular data for third-party applications without giving access to the full database itself.

Given these possibilities and especially the option for bi-directional third-party control of the system, Accolade® API's significantly facilitating the implementation into a given corporate IT landscape and enable different scenarios of use, including a data-centric approach like ITONICS Enterprise, but also a decentralized or complementary approach. The implications of this architectural freedom for the implementation of application for sustainable development planning are explained in section 3.3.

c) Specific roadmap software: Roadmunk by Roadmunk Inc. as an example for visualization software within existing project teams

As a tool with a modern graphical user-interface (GUI), Roadmunk was picked as an example for visualization software. Contrary to the aforementioned examples, the tool functionally focuses only on the visual part of technology roadmapping by means of a visual representation of the roadmap data and all corresponding process steps (reporting, visual examination, collaboration and feedback based on the TRM). If manual data-transmission workload by employees is to be avoided, the focus on these steps necessitates a third-party upstream system for raw data-collection, archival storage and automated logical connection between data objects, for example like the given ITONICS input modules. Furthermore, the raw-data needs to be formatted to *.csv or into a specifically formatted Excel sheet. However, if this requirement is met, Roadmunk offers a wide range of API's for collaboration- and project-management-tools like Asana, Trello and PivotalTracker (ROADMUNK, 2020c)

The creation and maintenance of roadmaps can be completely controlled externally by a GraphQL[11]-based API. With this query language, roadmap mutations become accessible by third-party implementations via high-level functions, like the following examples: (ROADMUNK, 2020b, 2020f)

- `deleteRoadmaps, updateRoadmap, createRoadmap`
- `deleteMilestones, updateMilestone, createMilestone`
- `deleteItems, updateItem, createItem`

There are more API-Implementations for authorization, feedback and idea queries and account management. These can also be tested on a so called GraphQL-Playground which is publicly accessible via a web-interface (ROADMUNK, 2020a, 2020d).

Once given the input data, Roadmunk offers several solutions for visualization of roadmaps (see Figure 28 and Figure 29) and corresponding employee tasks (see Figure 29), but also for idea prioritizing (see Figure 30) and captured feedback (see Figure 31).

Concludingly, Roadmunk serves as a software example that is specialized to a distinct part of technology roadmapping. Contrary to the aforementioned holistic tool collections, it functionally covers only the part of visualization. Within this distinct functional area however, it realizes a diverse range of facilitation potentials in terms of user-friendly solutions for all emerging process steps, interdepartmental cooperation of different teams and organizational implementation as it offers interfaces to popular project management tools. All interfaces to upstream- or complementary systems are statically defined, but well documented and therefore ensure a seamless integration of Roadmunk into a multi-tool workflow.

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[11] GraphQL is a query language for API's which, as a runtime to fulfil queries, describes the data within API's and the access to this data on a high level. (GRAPHQL, 2020)

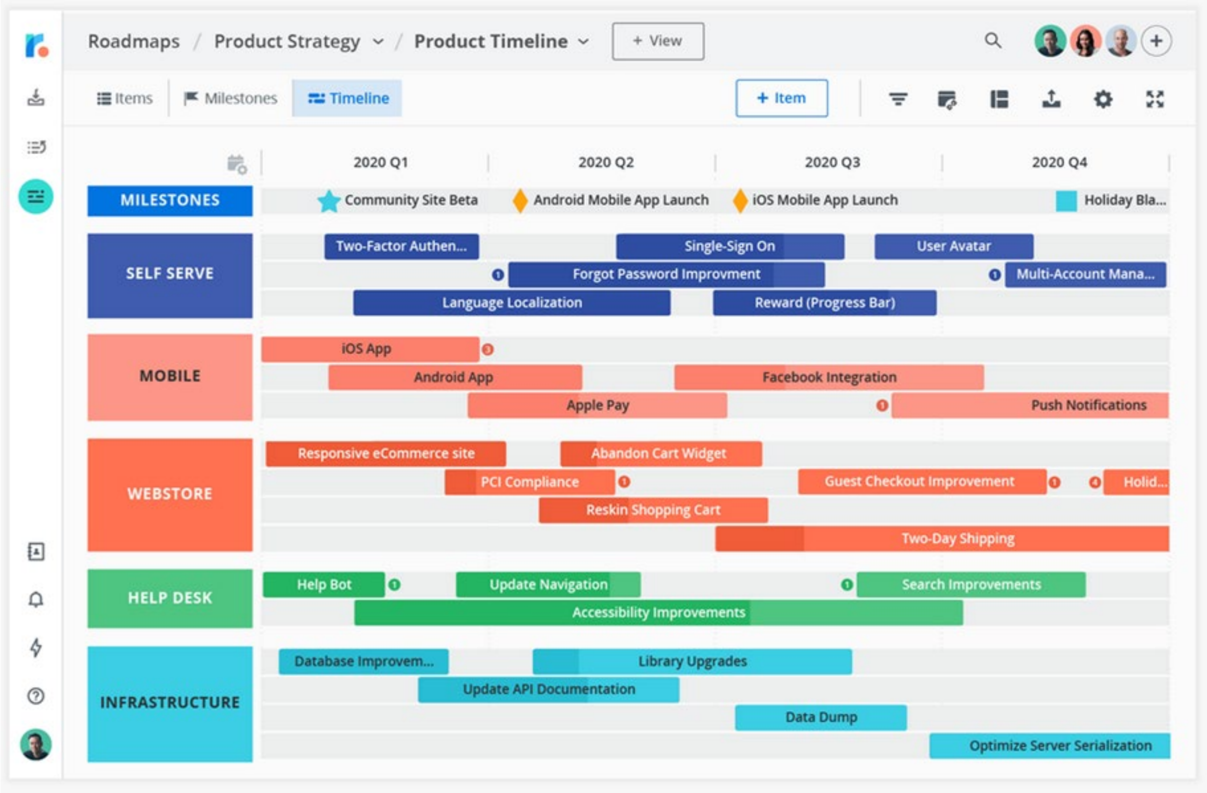
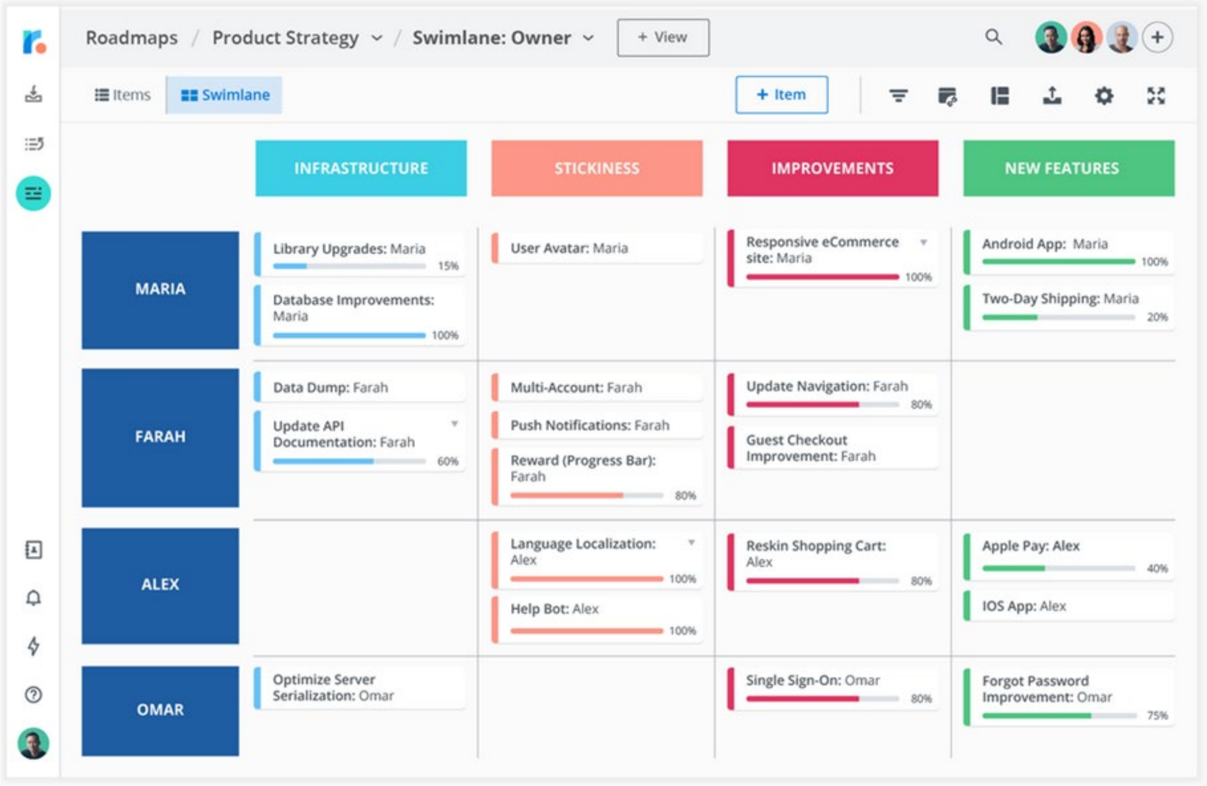
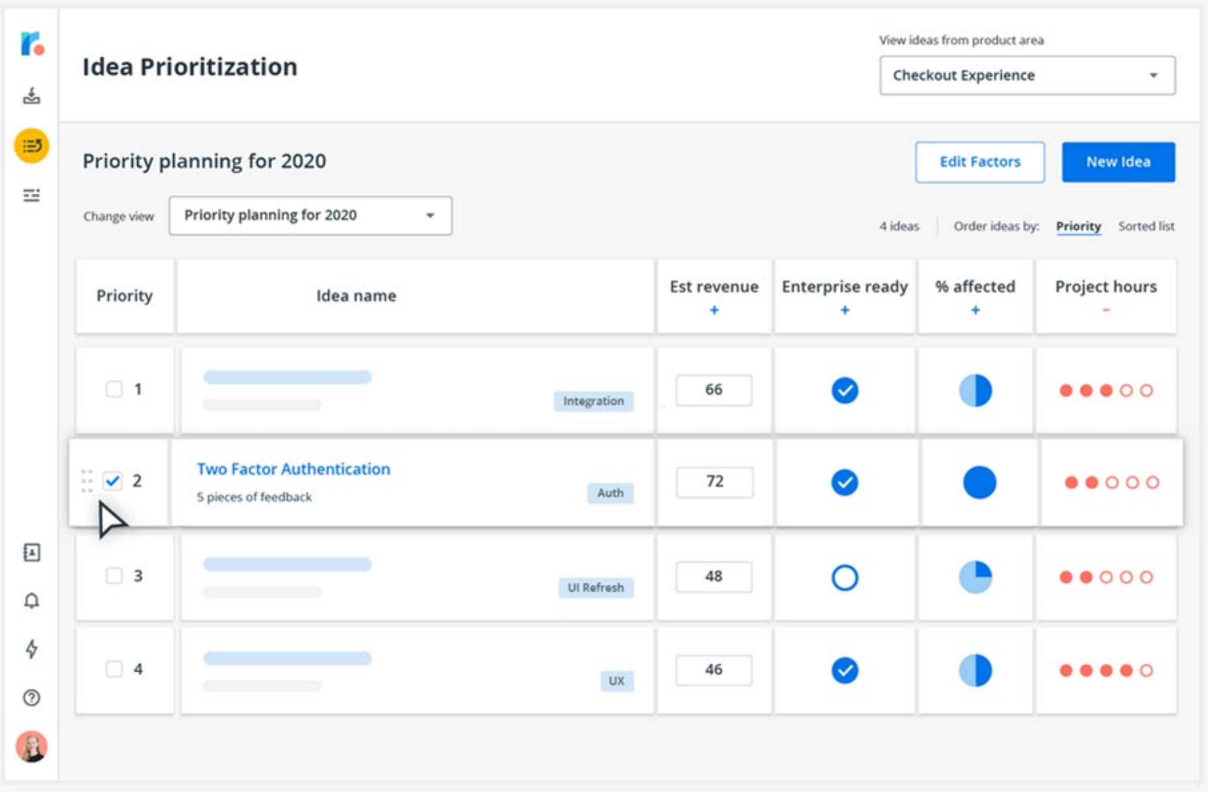


Figure 28 Example of a Roadmunk roadmap (ROADMUNK, 2020e)



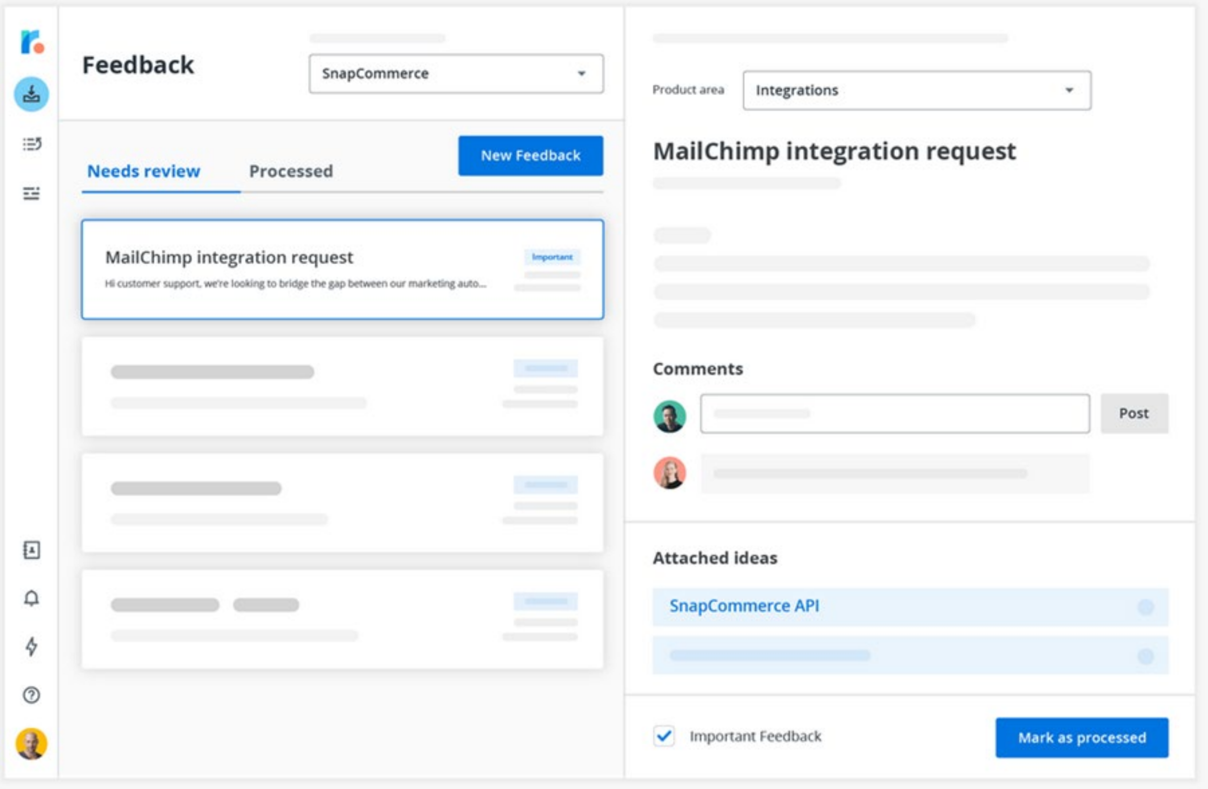
	INFRASTRUCTURE	STICKINESS	IMPROVEMENTS	NEW FEATURES
MARIA	Library Upgrades: Maria 15% Database Improvements: Maria 100%	User Avatar: Maria	Responsive eCommerce site: Maria 100%	Android App: Maria 100% Two-Day Shipping: Maria 20%
FARAH	Data Dump: Farah Update API Documentation: Farah 60%	Multi-Account: Farah Push Notifications: Farah Reward (Progress Bar): Farah 80%	Update Navigation: Farah 80% Guest Checkout Improvement: Farah	
ALEX		Language Localization: Alex 100% Help Bot: Alex 100%	Reskin Shopping Cart: Alex 80%	Apple Pay: Alex 40% IOS App: Alex
OMAR	Optimize Server Serialization: Omar		Single Sign-On: Omar 80%	Forgot Password Improvement: Omar 75%

Figure 29 Example for employee-based task view of a roadmap by Roadmunk (ROADMUNK, 2020e)



Priority	Idea name	Est revenue +	Enterprise ready +	% affected +	Project hours −
☐ 1	Integration	66	✓	◐	●●●○○
☑ 2	Two Factor Authentication 5 pieces of feedback Auth	72	✓	●	●●○○○
☐ 3	UI Refresh	48	○	◔	●●○○○
☐ 4	UX	46	✓	◐	●●●●○

Figure 30 Example of idea management by Roadmunk (ROADMUNK, 2020e)



Hi customer support, we're looking to bridge the gap between our marketing auto...

Figure 31 Example of a feedback interface by Roadmunk (ROADMUNK, 2020e)

d) Specific roadmap software: SharpCloud by SharpCloud Software Ltd. as an example of visualization software of complex data structures

As the second example for specific roadmap software, SharpCloud is at first sight yet another visualization tool within this context. Regarding the general functional coverage, it offers a wide range of different views for the imported data, inter alia including multiple layers, tabular views and bars, but also three-dimensional views (SharpCloud, 2020c).

The artefacts and views can be created and edited via the web-interface, the desktop client or a RESTful API. The API is extensively described with requests, parameters, responses, error codes and examples on a separated website. By using the API, a high level of automation can be achieved with common tools and platforms like Microsoft Excel and Microsoft Sharepoint or by using an automated data-transmission of *.xml or *.csv files (SharpCloud, 2019, 2020b; Sinclair, 2020).

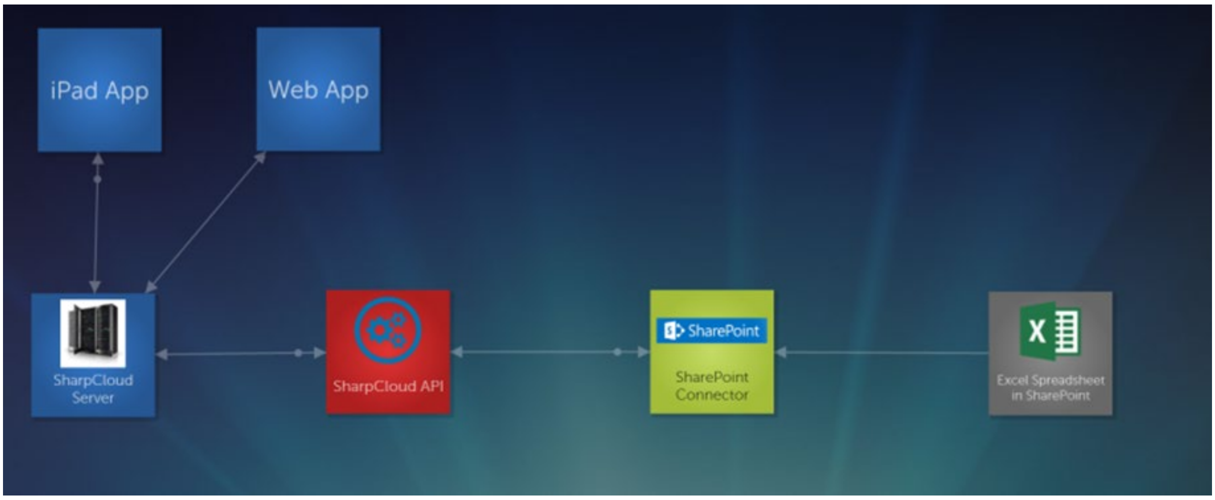
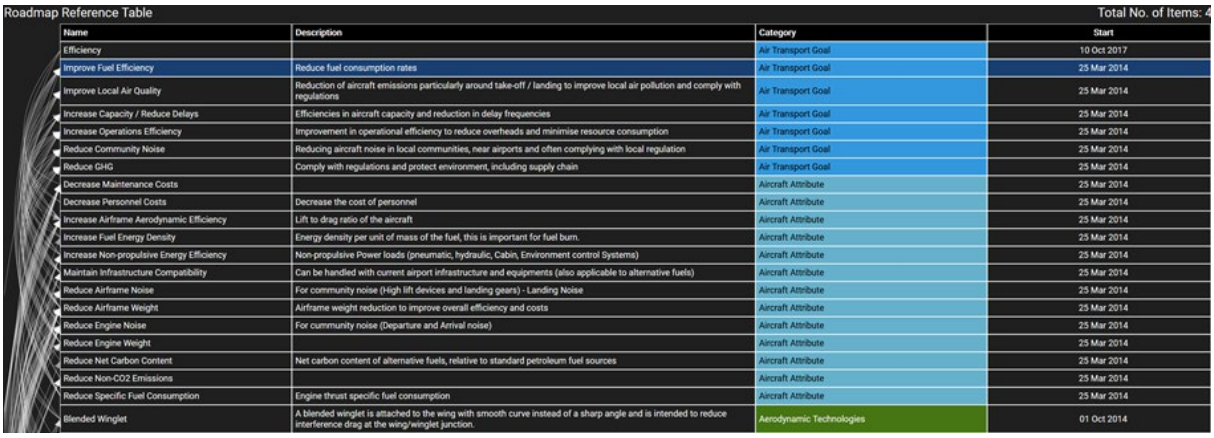


Figure 32 Example a data-flow by using the SharpCloud API (Sinclair, 2020)

However, while Roadmunk focused on project-management implementation, SharpCloud specialized on the representation of complex data. This specialization becomes evident, when retracing

- the reference table of a roadmap with all interrelations of artefacts (see Figure 33),
- the corresponding drill-down to show a single artefact and its connections (see Figure 34) and
- the following drill-through to see all information given for this specific artefact (see Figure 35).

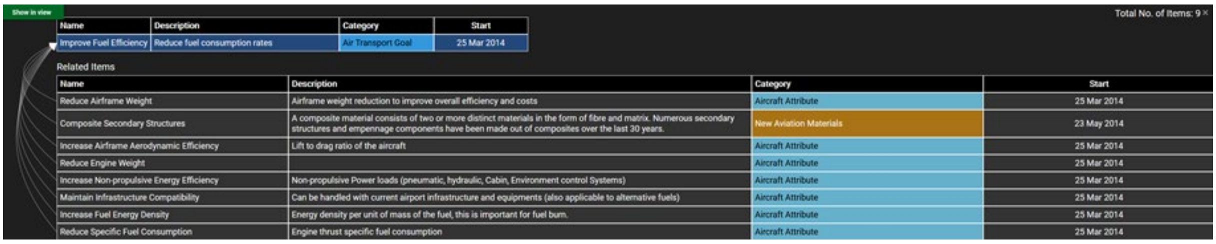


Roadmap Reference Table

Total No. of Items: 4

Name	Description	Category	Start
Efficiency		Air Transport Goal	10 Oct 2017
Improve Fuel Efficiency	Reduce fuel consumption rates	Air Transport Goal	25 Mar 2014
Improve Local Air Quality	Reduction of aircraft emissions particularly around take-off / landing to improve local air pollution and comply with regulations	Air Transport Goal	25 Mar 2014
Increase Capacity / Reduce Delays	Efficiencies in aircraft capacity and reduction in delay frequencies	Air Transport Goal	25 Mar 2014
Increase Operations Efficiency	Improvement in operational efficiency to reduce overheads and minimise resource consumption	Air Transport Goal	25 Mar 2014
Reduce Community Noise	Reducing aircraft noise in local communities, near airports and often complying with local regulation	Air Transport Goal	25 Mar 2014
Reduce GHG	Comply with regulations and protect environment, including supply chain	Air Transport Goal	25 Mar 2014
Decrease Maintenance Costs		Aircraft Attribute	25 Mar 2014
Decrease Personnel Costs	Decrease the cost of personnel	Aircraft Attribute	25 Mar 2014
Increase Airframe Aerodynamic Efficiency	Lift to drag ratio of the aircraft	Aircraft Attribute	25 Mar 2014
Increase Fuel Energy Density	Energy density per unit of mass of the fuel, this is important for fuel burn.	Aircraft Attribute	25 Mar 2014
Increase Non-propulsive Energy Efficiency	Non-propulsive Power loads (pneumatic, hydraulic, Cabin, Environment control Systems)	Aircraft Attribute	25 Mar 2014
Maintain Infrastructure Compatibility	Can be handled with current airport infrastructure and equipments (also applicable to alternative fuels)	Aircraft Attribute	25 Mar 2014
Reduce Airframe Noise	For community noise (High lift devices and landing gears) - Landing Noise	Aircraft Attribute	25 Mar 2014
Reduce Airframe Weight	Airframe weight reduction to improve overall efficiency and costs	Aircraft Attribute	25 Mar 2014
Reduce Engine Noise	For cummunity noise (Departure and Arrival noise)	Aircraft Attribute	25 Mar 2014
Reduce Engine Weight		Aircraft Attribute	25 Mar 2014
Reduce Net Carbon Content	Net carbon content of alternative fuels, relative to standard petroleum fuel sources	Aircraft Attribute	25 Mar 2014
Reduce Non-CO2 Emissions		Aircraft Attribute	25 Mar 2014
Reduce Specific Fuel Consumption	Engine thrust specific fuel consumption	Aircraft Attribute	25 Mar 2014
Blended Winglet	A blended winglet is attached to the wing with smooth curve instead of a sharp angle and is intended to reduce interference drag at the wing/winglet junction.	Aerodynamic Technologies	01 Oct 2014

Figure 33 SharpCloud reference table of a roadmap for an aerospace innovation roadmap (SharpCloud, 2020a)



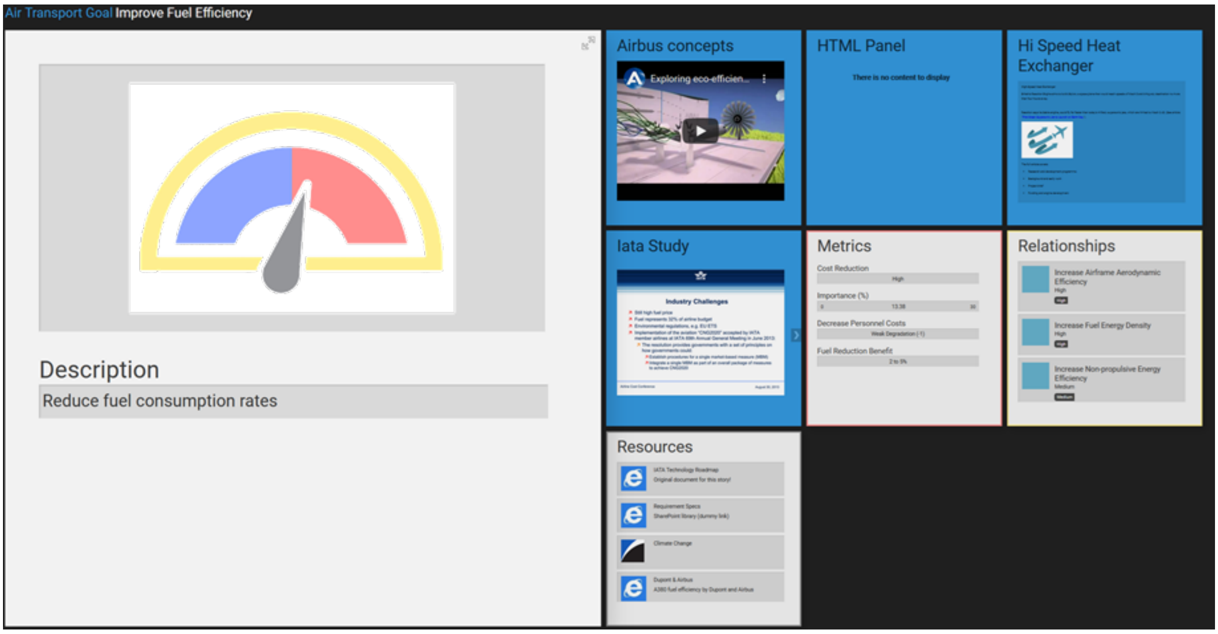
Total No. of Items: 9

Name	Description	Category	Start
Improve Fuel Efficiency	Reduce fuel consumption rates	Air Transport Goal	25 Mar 2014

Related Items

Name	Description	Category	Start
Reduce Airframe Weight	Airframe weight reduction to improve overall efficiency and costs	Aircraft Attribute	25 Mar 2014
Composite Secondary Structures	A composite material consists of two or more distinct materials in the form of fibre and matrix. Numerous secondary structures and empennage components have been made out of composites over the last 30 years.	New Aviation Materials	23 May 2014
Increase Airframe Aerodynamic Efficiency	Lift to drag ratio of the aircraft	Aircraft Attribute	25 Mar 2014
Reduce Engine Weight		Aircraft Attribute	25 Mar 2014
Increase Non-propulsive Energy Efficiency	Non-propulsive Power loads (pneumatic, hydraulic, Cabin, Environment control Systems)	Aircraft Attribute	25 Mar 2014
Maintain Infrastructure Compatibility	Can be handled with current airport infrastructure and equipments (also applicable to alternative fuels)	Aircraft Attribute	25 Mar 2014
Increase Fuel Energy Density	Energy density per unit of mass of the fuel, this is important for fuel burn.	Aircraft Attribute	25 Mar 2014
Reduce Specific Fuel Consumption	Engine thrust specific fuel consumption	Aircraft Attribute	25 Mar 2014

Figure 34 SharpCloud reference table for the improvement of fuel efficiency within a roadmap for an aerospace innovation roadmap (SharpCloud, 2020a)



Air Transport Goal Improve Fuel Efficiency

Description

Reduce fuel consumption rates

Airbus concepts

Exploring eco-efficien...

HTML Panel

There is no content to display

Hi Speed Heat Exchanger

Iata Study

Industry Challenges

Metrics

Cost Reduction: High

Importance (%): 0 13.38 30

Decrease Personnel Costs: Weak Degradation (-1)

Fuel Reduction Benefit: 2 to 5%

Relationships

Increase Airframe Aerodynamic Efficiency – High

Increase Fuel Energy Density – High

Increase Non-propulsive Energy Efficiency – Medium

Resources

IATA Technology Roadmap – Original document for this story!

Requirement Specs – SharePoint library (dummy link)

Climate Change

Dupont & Airbus – A380 fuel efficiency by Dupont and Airbus

Figure 35 SharpCloud artefact information for the reduction of fuel consumption rates within a roadmap for an aerospace innovation roadmap (SharpCloud, 2020a)

With this example and the depth of included data interrelations in mind, all connections and filtered views can be retraced online with almost immediate feedback of the GUI, even when creating a three-dimensional roadmap, in this example with applied filters for “ethical” or “social” drivers (see Figure 36).


3D View - Showing Priority by Category by Impact

INTERACTIVE FILTERS

Categories: ☐ Advanced Apps ☑ Transformational Tech ☑ Software ☑ Hardware

Tags: NOT OR AND

Driver: Ethical, Social (selected); Global, Innovation, Threats

Figure 36 Three-dimensional SharpCloud relationship chart with applied filters (SharpCloud, 2020c)

Even in comparison to the aforementioned enterprise software-tools, the possible view-manipulations (different views, filtering, drill-down, drill-through, etc.) are notably extensive and at this point not further examined (SharpCloud, 2020a).

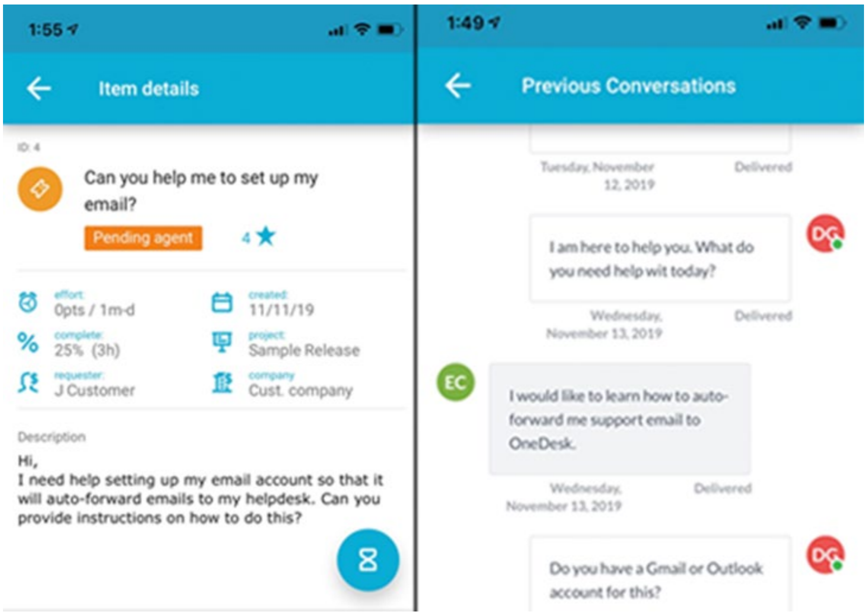
On the one hand, the data-navigation methods enable the roadmap-contributor to quickly orientate within the complex data environment and find and edit the point (or view) of interest. On the other hand, an interested technology manager can quickly find specific information and visualize relationships. In every case, a substantial preceding workload is needed to set-up the data-structure of this environment and preliminary knowledge of technology roadmapping is presupposed. That’s why the facilitation potential regarding the organizational implementation is considerably lower in comparison with the aforementioned tools.

However, referring to the methodological classification of the found technology roadmaps based on automation in section 2.2.3, SharpCloud offers a unique processual facilitation potential when it comes to automated visualization of complex interrelations. While the visualization of aforementioned tools is limited to their given data-structures, the visualization of SharpCloud can be completely automated on the basis of the self-defined perspective structure of the user. This mechanism can be used to automate the implementation of whole new perspectives and therefore corresponds to type c) of section 2.2.3. As a result, linear scaling of the TRM with rising requirements and perspectives can be achieved without an exponential rise of workload due to complexity. However, the task of necessary information-sourcing for new perspectives remains at this point.

Concluding, beside the specialization on data-warehouse functionality and extensive data-visualization, SharpCloud enables an interdepartmental cooperation by giving the option for strict separation of data registration by data-scientists and further processing within technology roadmapping by innovation managers. This is highlighted, as additional distributed domain experts can be included in the process demand-based and without the actual need of special knowledge of the method of technology roadmapping itself. The facilitation potential regarding the involvement of people is still difficult to evaluate, as no dedicated modules or third-party implementations for this purpose were found.

e) Complementary Software: OneDesk by OneDesk Inc. as an example for customer feedback management as the input for innovation planning

Though OneDesk can be used as a roadmapping tool for simple projects, its functional focus is set to the efficient involvement of internal teams and external feedback. This facilitation



Can you help me to set up my email?

effort: 0pts / 1m-d
created: 11/11/19
complete: 25% (3h)
project: Sample Release
requester: J Customer
company: Cust. company

Hi,
I need help setting up my email account so that it will auto-forward emails to my helpdesk. Can you provide instructions on how to do this?

Tuesday, November 12, 2019 Delivered

I am here to help you. What do you need help wit today?

Wednesday, November 13, 2019 Delivered

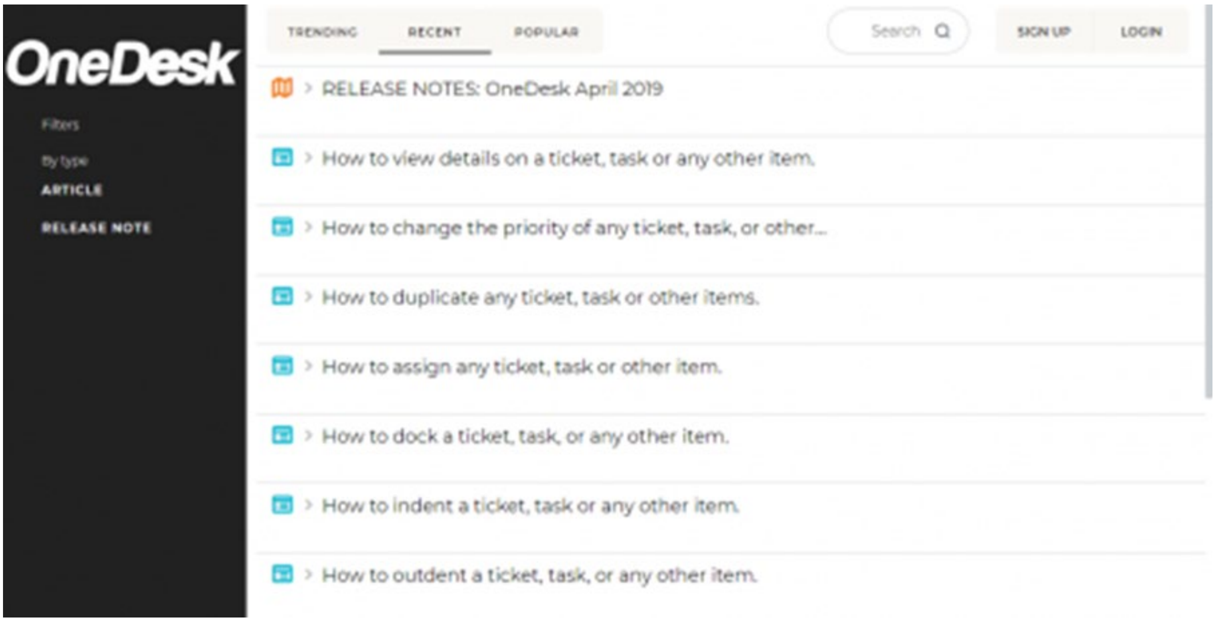
I would like to learn how to auto-forward me support email to OneDesk.

Wednesday, November 13, 2019 Delivered

Do you have a Gmail or Outlook account for this?

Figure 37 **Chatfunction as part of the OneDesk helpdesk (OneDesk, 2020e)** potential is achieved by a combination of helpdesk- and project-management functions, that furthermore can be automated (OneDesk, 2020c).

In this way, a customer-facing live chat can be used to directly generate a ticket which can be viewed by the customer but also is sent to the project team. After ticket completion, the solution can be transformed into knowledgebase article which can be seen by customers as well. In this knowledgebase, customers can search for previous generated information and frequently asked questions or topics can be reduced over time. Several combinations and automations of the aforementioned steps are possible, however (OneDesk, 2020a, 2020b).



> RELEASE NOTES: OneDesk April 2019

> How to view details on a ticket, task or any other item.

> How to change the priority of any ticket, task, or other...

> How to duplicate any ticket, task or other items.

> How to assign any ticket, task or other item.

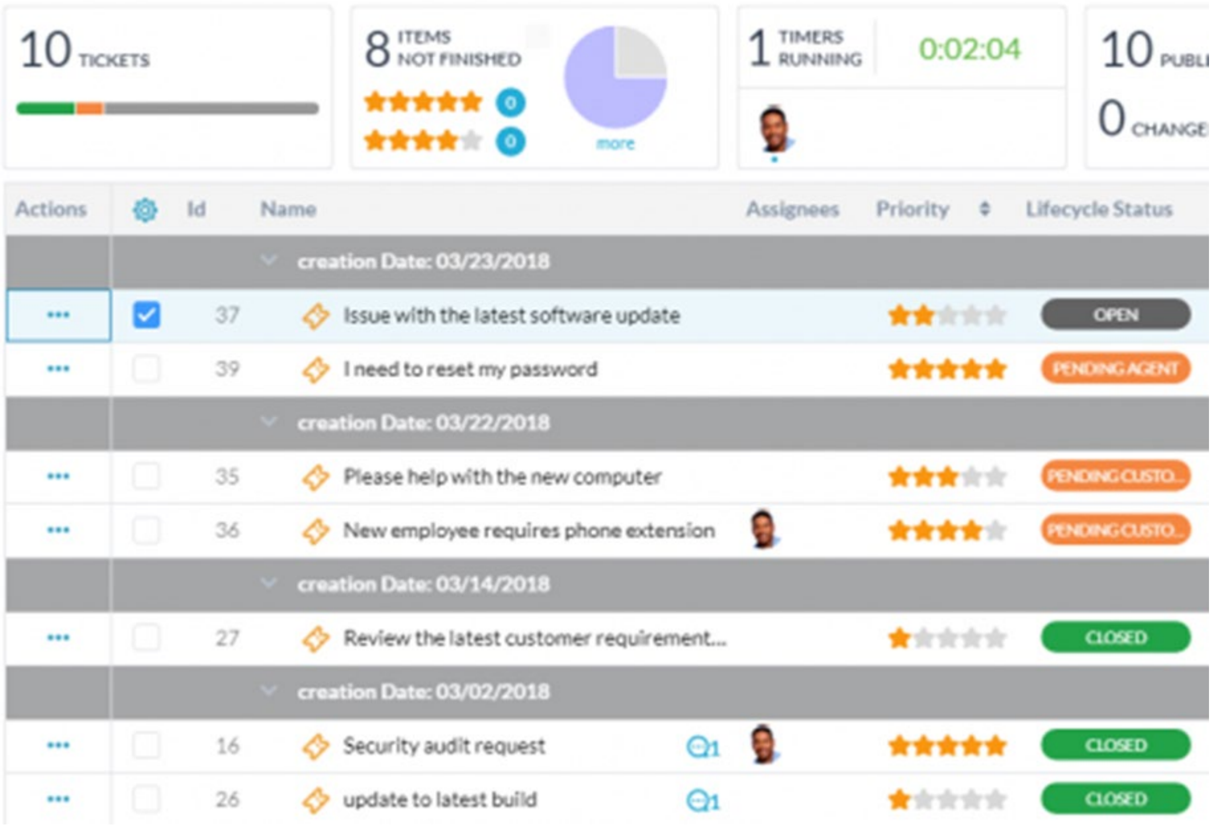
> How to dock a ticket, task, or any other item.

> How to indent a ticket, task or any other item.

> How to outdent a ticket, task, or any other item.

Figure 38 Example of a knowledgebase for frequently asked questions by OneDesk (OneDesk, 2020b)

When it comes to the involvement of internal employees, OneDesk offers a range of task-management tools, implementation for mail- and file-sharing-tools, summaries and dashboard-views to efficiently keep track on existing customer tickets (OneDesk, 2020c, 2020e).



Actions	⚙	Id	Name	Assignees	Priority	Lifecycle Status
			creation Date: 03/23/2018			
•••	☑	37	Issue with the latest software update		★★☆☆☆	OPEN
•••	☐	39	I need to reset my password		★★★★★	PENDING AGENT
			creation Date: 03/22/2018			
•••	☐	35	Please help with the new computer		★★★☆☆	PENDING CUSTO...
•••	☐	36	New employee requires phone extension		★★★★☆	PENDING CUSTO...
			creation Date: 03/14/2018			
•••	☐	27	Review the latest customer requirement...		★☆☆☆☆	CLOSED
			creation Date: 03/02/2018			
•••	☐	16	Security audit request 1		★★★★★	CLOSED
•••	☐	26	update to latest build 1		★☆☆☆☆	CLOSED

Figure 39 OneDesk overview of customer tickets (OneDesk, 2020e)

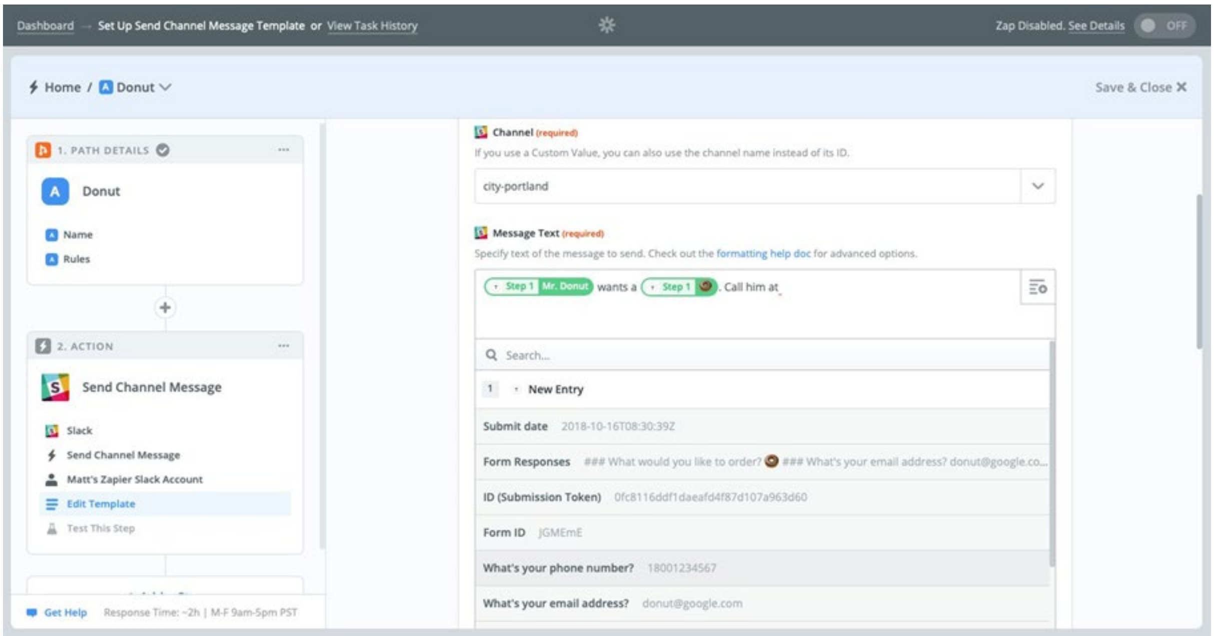
Additionally, to this functional coverage, OneDesk was implemented in the synopsis of software tools as a complementary software, because of the way it focuses on the involvement of external input automation. This may help at later process steps of technology roadmapping, as internal and external questions and additional input to shared TRM can be easily tracked and worked into subsequent versions of the TRM. Especially for the use in an open innovation scenario, OneDesk greatly facilitates the involvement of people. This is also shown in the licensing policy. While the pricing of the aforementioned tools scales with user count and includes a declining list of features when it comes to cheaper license models, OneDesk solely calculates its licence fees by internal user count and does not differentiate in functional coverage at all (OneDesk, 2019).

Summarizing, OneDesk offers implementations and tools, to efficiently capture external feedback at later technology roadmapping stages and seamless integrate it in a project’s workflow. Though it does not offer extensive API integrations, it includes a *.csv im- and export as well as interfaces to common project and task management tools and therefore can easily be integrated into an existing organizational workflow. Moreover, this implementation is simplified by the implementation of a Zapier interface, which is described followingly (OneDesk, 2020c, 2020d).

f) Complementary Software: Zapier by Zapier Inc. as an example for workflow automatization

Application interfaces and their automatization were, up to this point of the synopsis, part of the functional coverage of the aforementioned tools. Because of this, Zapier was included as a tool to facilitate the automatization of data transmission between different tools of an existing workflow.

Condensed, Zapier is a tool to create unsupervised workflows that connects multiple applications in terms of information transmission and action execution. This is done without the necessity to program algorithms via a coding language, as all workflows, or so called *"Zaps"*, are created with a web interface with pre-defined forms. A *Zap* is defined as an automated workflow that is started by one or more triggers or events within apps, and consecutively executes tasks. While defining the triggers and tasks in the web form, pre-defined and app-specific information blocks are provided by over 2000 app-interfaces, for example the task- and corresponding employee name of a completed Asana task. Furthermore, Zaps can be expanded by conditional tasks and different execution paths, which enables the user to create more complex workflows (ZAPIER, 2020b, 2020d, 2020e).



Channel (required)
If you use a Custom Value, you can also use the channel name instead of its ID.
city-portland

Message Text (required)
Specify text of the message to send. Check out the formatting help doc for advanced options.
Step 1 Mr. Donut wants a Step 1 🍩. Call him at

1 New Entry
Submit date 2018-10-16T08:30:39Z
Form Responses ### What would you like to order? 🍩 ### What's your email address? donut@google.co...
ID (Submission Token) 0fc8116ddf1daeafd4f87d107a963d60
Form ID JGMEmE
What's your phone number? 18001234567
What's your email address? donut@google.com

Figure 40 Example for Zapier paths user interface (ZAPIER, 2020b)

While Zapier alone offers no functions for roadmapping, its facilitation potential regarding the implementation of other applications within the corporate environment is wide ranging. Especially project- and task-management tools can be connected to and with Zapier via several pre-defined implementations, which facilitates the involvement of people as well. API's to not implemented new software tools can be created user-friendly with a visual API-builder or a command line interface of Zapier. Either way, the necessary preliminary programming knowledge is minimized and the implementation time is shortened (ZAPIER, 2020a).

The aforementioned concepts of Zapier not only can be used to connect previously unconnected tools in an existing corporate IT environment, but furthermore automate the information flow needed for a full workflow automation with a two to 15 minute information update-intervals between applications (ZAPIER, 2020c).

Thus, a continuous digital workflow like given in corporate standard software, is realized in a modular way with different third-party applications. This concept enables more complex IT architectures along a digitalized technology roadmapping and an automated integration of sustainable development planning tools, which is further examined in section 3.3.

3.2 Synopsis of Software Tools supporting Sustainable Development Planning

Given the definition of sustainable development in section 2.1.3, the examples of software tools are classified according to their facilitation potential. In detail, the methods that facilitate an intentional change of the company to fulfil the future needs by the current society considering limited environmental capabilities are examined. Regarding the functional coverage, all tools for sustainable development planning may, apart from the research question, be categorized into one of the three given aspects of section 3.1.1 (corporate standard software, specialized software and complementary software).

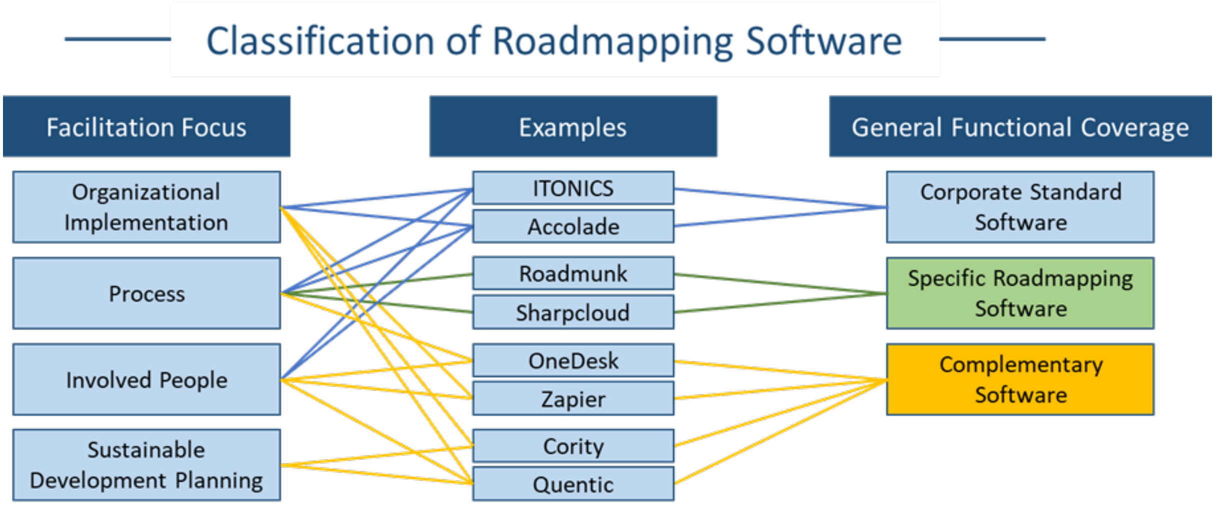


Figure 41 Expanded synopsis of software tools supporting technology roadmapping and sustainable development planning (based on Isenmann, 2008)

However, with the research question in mind, all examined software tools in this section are classified as complementary software in relation to their supportive function to implement aspects of sustainable development in technology roadmapping. With this delimitation, Figure 23 is expanded by two examples of software tools supporting sustainable development planning (see Figure 41).

Following, these two tools for environment, health and safety (EHS) management will be analysed.

a) Complementary Software: Cority by Cority Software Inc. as an example for EHS management software with focus on risk management

As the first example, Cority was chosen as a comprehensive tool for EHS management. Due to the research question, an all-embracing analysis is resigned and special attention is given to the environmental aspects of the tool. Cority has a modular application architecture and consists of modules for: (Cority, 2018b)

- Environmental management
- Occupational health software
- Ergonomics
- Industrial hygiene
- Safety management
- Quality management
- Hospital employee health

The module for environmental management is offering solutions and metrics for several aspects of sustainability: (Cority, 2018a)

- Air emissions
- Water management
- Chemical management
- Waste management
- Compliance management, inspections and audits
- Change management
- Business intelligence

Especially the integration of measures for change management and business intelligence are used to integrate Cority into an existing corporate organization and digital environment and facilitating the intentional change of a company towards sustainability. To do so, Cority is offering a set of processes that can be set up within the tool and after implementation automatically be tracked. At this point, attention is given to the data quality, as Cority is offering an own so called “data quality score” to ensure that the used data for further processing is trustworthy.

Especially for legislative compliance and reporting, this method is saving time for periodic manual information updates, that are presumed by many compliance management systems (Cority, 2017).

On the digital side, the tool implementation can be done via predefined API's or *.csv im-/export. With this in mind, tool-assisted multi-source evaluations of environmental incidents can be simulated and risks, results and countermeasures be defined. These so called "What-If" analyses are executed by Cority in realtime and with an own developed prediction engine (Cority, 2017).

Summarizing, Cority is offering a comprehensive platform for a risk- and compliance-based integration of sustainable aspects. Especially the "data quality score" and "what-if"-scenario evaluation is facilitating the use of Cority as a complementary software and extensive information source for technology roadmapping. To chronologically integrate sustainability targets into TRM, a compliance calendar with audits and commencements of acts can be used in addition.

b) Complementary Software: Quentic by Quentic GmbH as an example for EHS management software with the focus on corporate social responsibility and KPI's

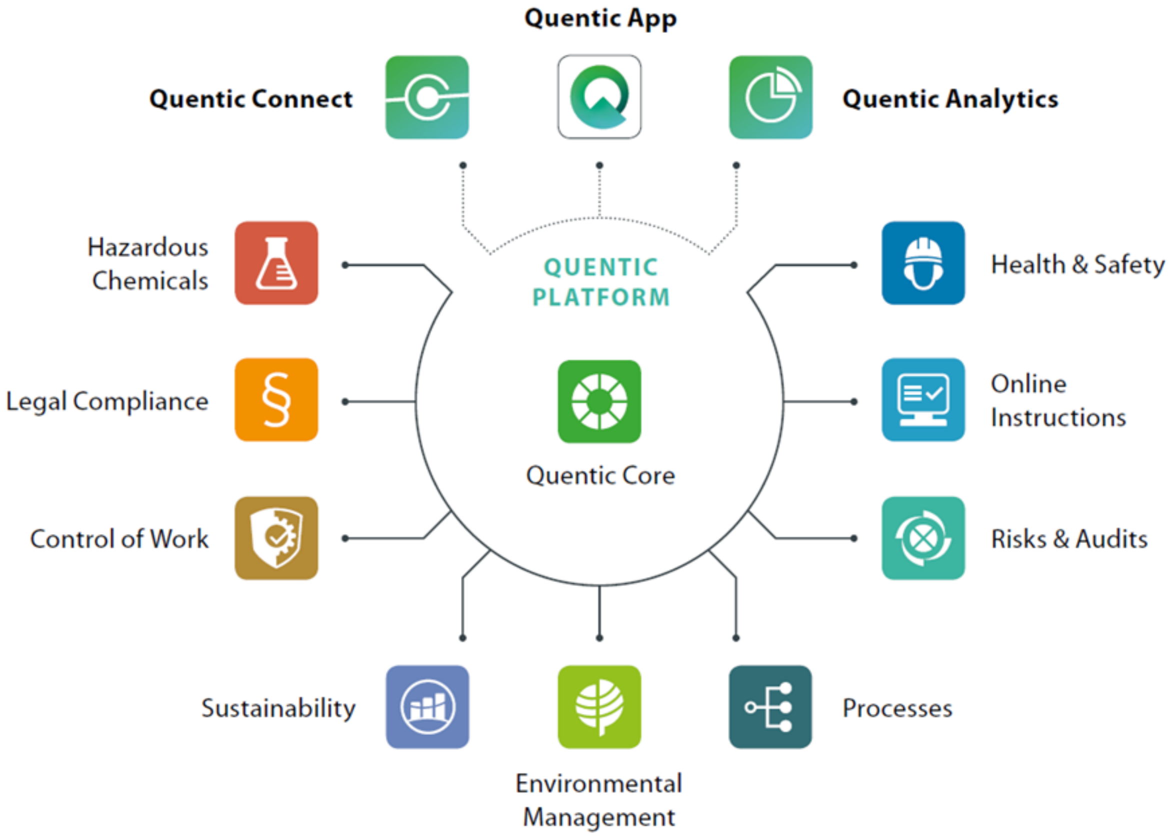


Figure 42 Functional coverage of Quentic (Quentic, 2020b)

As the second example for EHS software, Quentic as well a comprehensive tool for most EHS issues regarding legal compliance and corresponding management systems. The general functional coverage of the tool is subdivided into modules and can be seen in Figure 42. Out of the depicted modules, special attention is given to the sustainability module as well as the data modules *Quentic Core, Quentic Connect* and *Quentic Analytics.*

As other modules, the sustainability module is mainly targeted to assure the compliance regarding legal requirements and reports. This is done by defined standardized data-structures and catalogues that contain certain environmental KPI's. Once set up, the investigation, data quality evaluation, processing and reporting of these indicators can be realized within the tool. Additionally to the ecological aspects, sustainability is perceived as a social and economic issue. Therefore, stakeholder communication with different levels of access authorization and real-time monetary unit conversion is integrated as well (Quentic, 2020d).

With *Quentic Connect, Quentic Core and Quentic Analytics*, the data processing between modules and to third-party applications is automated and standardized. With the *Connect* Module, external information is imported and qualitatively checked for errors or anomalies. The several application integrations facilitate the organizational implementation of Quentic and ensure timeliness of data (Quentic, 2020a).

An exemplary overview of supported applications can be seen in Figure 43.

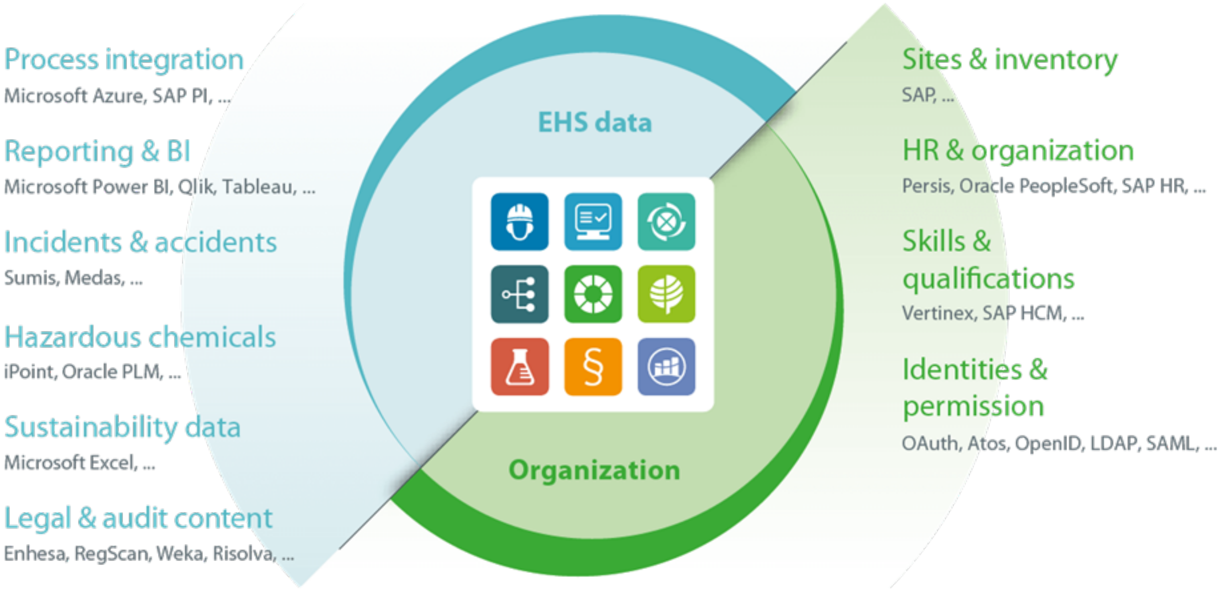


Figure 43 Third-party application options in Quentic Connect (Quentic, 2020a)

When the data is imported, the central processing is done by Quentic Core. In this module, data records like documents, roles and actions are centrally mapped. This enables action planning, root-cause analyses of incidents, digitally represented site structures and simulations. All other Quentic apps are based on the Core module and are connected to it (Quentic, 2020c).

In comparison to Cority's risk-based approach, Quentic orients more on KPI-reporting and inclusion of stakeholder. This implies the will to transparently track inter alia environmental KPI and compare them among sites and departments as well as with their respective previous values. With this approach, quantified goals can be derived and ecologic target values can be handled tantamount to economic ones, as needed for the implementation in technology roadmapping. The fully automated control cycle of extensive third-party data-import, KPI derivation and evaluation and data-export is facilitated by the aforementioned Quentic modules *Connect*, *Core* and *Sustainability*. Regarding the methodological classification based on automation of technology roadmapping in section 2.2.3, this enables a fully automated integration of sustainability as an additional perspective in technology roadmapping.

3.3 Architecture of an IT based Framework supporting Technology Roadmapping striving for Sustainability

In the preceding sections, an overview was given of *if* and *how* sustainability is integrated into TRM by a systematic literature review and a synopsis of IT tools that facilitate technology roadmapping and sustainable development. This preliminary work is now brought together to examine the research question, how an IT framework may facilitate technology roadmapping and the implementation of sustainability in general.

A central insight of the systematic literature applied to the degree of automation in the roadmapping process and the implications of manual workload in frontloading activities, TRM creation activities and TRM maintenance activities. It was shown, that while integrating sustainability as an additional perspective to technology roadmapping, the rising complexity was mostly accompanied by appropriate measures of process automation to extenuate the exponential rise of manual workload (see section 2.2.3).

However, to exploit the full potential of process automation, special attention is to be given to a seamless digitalized workflow, as every necessary manual interface between systems[12] offers leeway for general technology roadmapping mistakes, like obsolete information that is forgotten to be updated by the employee. If the process is digitalized and automated, a wide range of interdependent facilitation potentials can be achieved by IT tools (see section 3.1.2). Consecutively, this substantiates the disregard of unconnected IT tool workflows in this section.

Like a common abstract language, the unsupervised and automated communication between IT tools or systems necessitates a standardized information-transmission, as either API, data-

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[12] By manual interface at this point, every interface is defined that necessitates human interaction to transmit data or information from one system or workstep to another.

type or protocol needs to be common to even enable a communication. For this function, some of the examined tools already implemented a specialized third-party interface.

To systematically investigate into IT framework concepts that facilitate an automated integration of sustainability by the use of a bi-directional data transmission, three different approaches to standardized information-transmission with integrated technology roadmapping and sustainability planning tools are now examined.

The main difference between these approaches is the localization of the main data source (the so called “single point of truth”) and if and where the data is transformed for transmission, to ultimately standardize information for the use of technology roadmapping. Therefore, three approaches are differentiated:

- Decentralized information approach with standardized interfaces (see section 3.3.1)
- Decentralized information approach with standardized data-preparation (see section 3.3.2)
- Centralized information approach with standardized database (see section 3.3.3)

To systematically highlight the differences in IT architectures, every tool within the architecture is subdivided into four layers:

- The **view-layer** is best described as the graphical user interface and includes all visible objects of the tool as well as their corresponding software-functions that translates user-input into tasks or show the user that a certain event happened by translating tool-internal information into visible information.[13]
- The **model-layer** holds all information of the tool and operates as the tool-internal database.
- The **control-layer** processes software-requests (user- or event-triggered) and operates as the logic-centre of the tool. It does not hold the result of the processed request, but either stores it into the model layer or returns it into the view-layer.
- The **interface-layer** is, depending on the use, a mixed class of the control-layer and the model layer. It operates as an interface to third-party applications by translating requests from the control-layer into API-specific instructions and vice versa relays translated incoming API-specific instructions to the control-layer. This may be combined with a data storage to save diverse information of different connected tools in a standardized form.

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[13] For the purpose of visual simplification, the visual layer of exisitng corporate software is left out in the following figures

One the basis of these layers, the three approaches are now examined.

3.3.1 Integration of Sustainable Development Planning Tools in a decentralized Information Approach with Interface-Standardization

Starting with the least centralized[14] approach to information standardization in terms of data storage, the decentralization of information can be realized in two ways. Both have in common, that the reliable source of information is localized in the decentralized tools and the synchronization trigger has to be created within the TRM-tools by requests to those decentralized tools, in order to realize an automated data-synchronization and bi-directional communication.

The first concept, that needs no additional third-party applications and set-up effort is the interface standardization without any intermediary tools and is depicted in Figure 44. To explain the specifics, the general structure of the following figures is explained first:

- The **process of technology roadmapping** is symbolically illustrated on the left side of the picture
- As **different TRM software tools** are accessed by different steps within the process of technology roadmapping, the connection between steps and tools is simplified and the given tools in the middle of the figure are exemplary listed.
- On the right, different kind of **existing corporate tools** are depicted that can be assigned to accompanying or complementary software in the general corporate IT environment.
- The **tools for sustainable development planning** that need to be implemented to form a basis for the data-driven implementation of sustainability in technology roadmapping are consecutively classified as complementary software for both, the corporate and the technology roadmapping perspective. However, as no dedicated tool for sustainability in technology roadmapping was found, the corresponding green block was localized on the right side for complementary corporate software of the picture.
- **API's** are characterized by their shape. Different shapes correspond to different API's and respective communication protocols and methods.
- The same applies to **data-models**, as different shapes correspond to different data-types or information-structures in general. Moreover, this implies that in order to

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[14] With the research questions in mind, technology roadmapping is referred as the central process in this thesis. Consecutively, all TRM-tools are referred as central tools and all complementary or existing corporate tools are referred as decentralized. Thus, decentralized data storage in this context is expressing a scenario in which the reliable data source is outside the TRM-tools.

transmit data from tools of different data-models, the data needs to be transformed into the correct model as well. [15]

- **Highlighted in red**, characteristics that imply additional effort while setting up the specific IT Framework are explained for each figure.

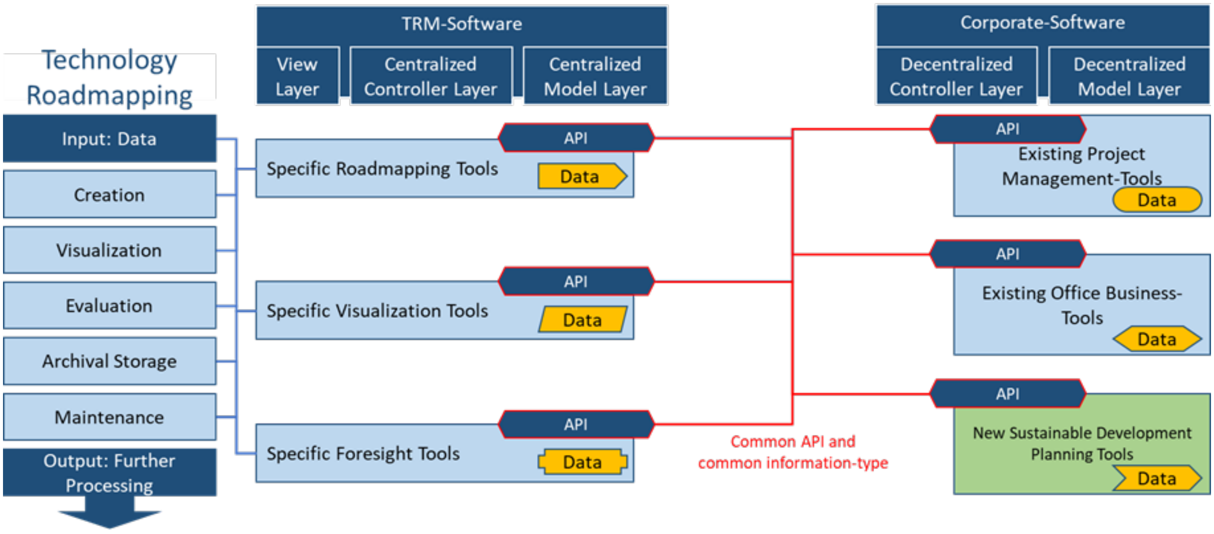

Figure 44 Integration of sustainable development planning tools in a decentralized information approach with interface standardization (Source: personal collection)

As seen in the above figure, all tools need to be carefully chosen to have the same API in common. Any derivation from this requirement would necessitate a step or tool in between. With the given common API, all tools can communicate with each other and hold their own information model in the respective layer. As mentioned, the synchronization of data is to be realized by TRM-tools to ensure that the centralized model-layer is storing the same information as the decentralized model layers of the corporate and sustainable development tools.

If a mutual high-level third-party API implementation exists for all communicating tools, this approach ensures a comprehensive information-standardization and a fully digitalized workflow, if all tools are chosen by this criterion.

However, if the API is standardized at a lower level (e.g. if only the protocol and the request-handling is standardized, but not the request and the information of the response), the mutual understanding of data-structures, request and responses must be implemented twice - for each participant of a bi-directional communication channel. Subsequently, this implies an

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[15] A simple example for this case is given, if different metrics are used in two connected tools for the same object. In order to use the “foreign” information of the other tool, the values need to be adapted to the “native” metric system first. This applies as well for more complex relationships, like different quantity or quality of data or information about grouped objects is brought together with information of single objects.

exponential growth of necessary mutual communication implementations by a rising number of connected tools.

To avoid this effect, a centralized interface software can be implemented into the IT framework. An example of this kind of software was given by Zapier in section 3.1.3. With such a tool, even a connection of tools with different API's can be realized, as the interface standardization effort is moved into the centralized interface tool. This framework concept is depicted in Figure 45.

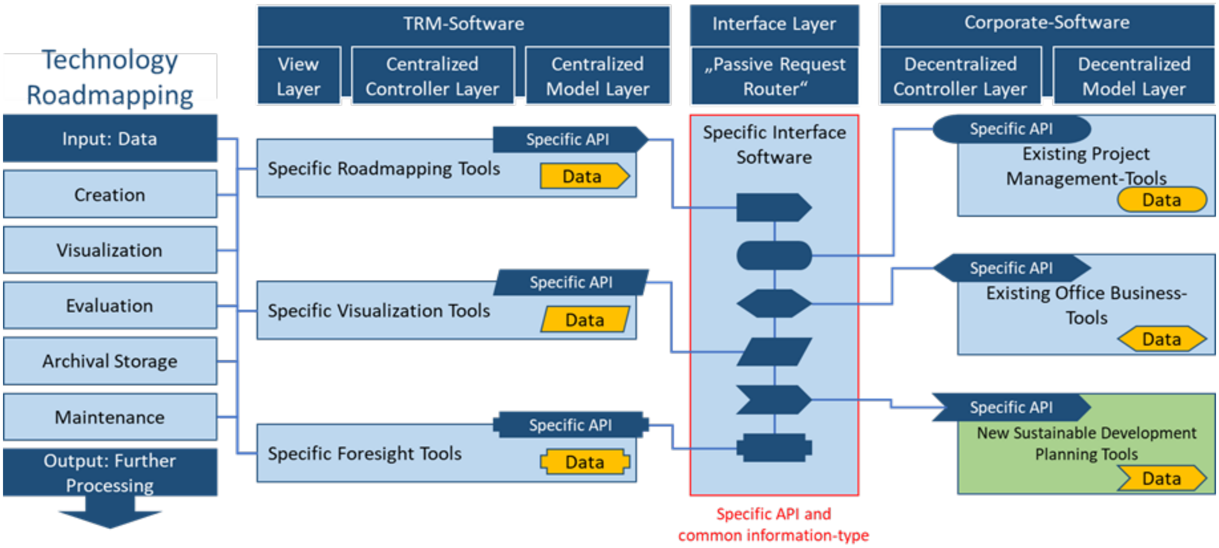

Figure 45 Integration of sustainable development planning tools in a decentralized information approach with centralized interface-software (Source: personal collection)

In this case, Zapier acts like high-level third-party API implementations for the connected applications and ensures a common understanding of requests, responses and included data-models. Still, all information-communication-connectors between two applications must be defined once in the central interface tool (by the example of Zapier, these are called "Zaps", see section 3.1.3), as no information is stored in the interface layer. By this concept, the interface layer acts like a network-router that relays requests and responds to the correct port according to its routing table. In the example of Zapier, the sum of all Zaps corresponds to this routing table, while the request is additionally translated into the corresponding API-language.

As for all centralized approaches, this creates a dependence on the interface tool, developed internally or bought as third-party software, as well as its performance. As a result for the specific abovementioned approaches, a transmission can solely be realized if all API's and data-models are known by the requesting and interfacing tools. This affects the implementation of SD-planning tools in the workflow, as knowledge of external data-models (f.e. environmental parameters) and data-model-transformation is still to be implemented either in the TRM or SD tools to use the new data for roadmapping.

Summarizing, the implementation effort for this approach is highly dependent on the kind and count of API's and existing data-models of the connected tools. The more these are of the same kind, the less implementation effort has to be done in order to realize a seamless digitalized workflow. Speaking of the integration of SD-tools, this approach facilitates the *connection* of respective tools only, but not the *usability* of SD-data inside connected TRM tools. Therefore, the facilitation potential of this framework architecture regarding the integration of sustainable development planning is comparably less given than in the following approaches.

3.3.2 Integration of Sustainable Development Planning Tools in a decentralized Information Approach with centralized Data-Preparation

While in section 3.3.1 no data was stored in the interface layer and the information source was decentralized, all data transformation had to be done in the requesting or responding decentralized tools as well. To avoid this, a centralized data-warehouse can be implemented as an interface layer in the IT framework (see Figure 46).

Contrary to the bilateral requests of the aforementioned approach, the TRM-tools requesting data from the centralized data-warehouse with no knowledge of the original data source.

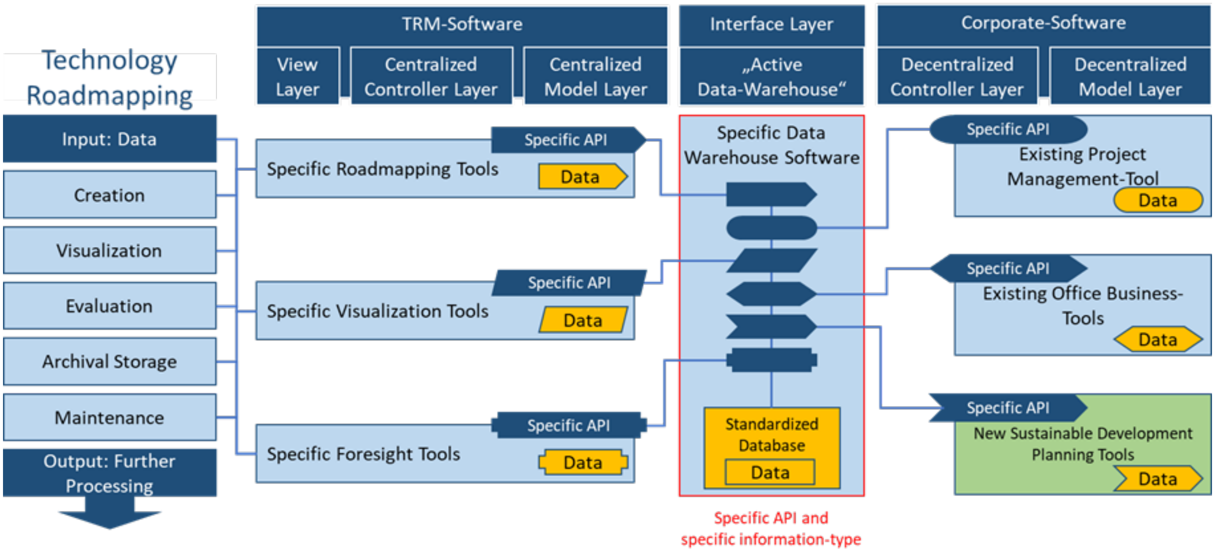

Figure 46 IT framework with centralized data-preparation (Source: personal collection)

The implemented data-warehouse must as well comply with the same API-requirements as the centralized interface layer to be connected to the existing corporate IT environment and TRM tools. When the connections are set up, all data-transformation is to be done in the central data warehouse. In the case of the implementation of SD-planning tools, the environmental parameters and goals have to be mapped to the strategic targets just as the economic and regulatory parameters.

While the interface layer in section 3.3.1 operated as a passive router, the data-warehouse can be implemented in an active way to automatically synchronize its data by requests to the connected third-party applications. At this point, a distinction is made regarding the role of the stored data in the interface layer:

- If the tool is solely used as a centralized data preparation point to **consolidate data** of different data sources, the information stored in the tool itself may be considered as just a copy of the decentralized stored information. This implies that the true source of information still remains decentralized and the connection to it is unidirectional.
- If the consolidated data is used to create new insights as **meta-data**[16] which have an impact on the original data-source, these insights can be returned to the original tools and their respectively stored data. This implies, that the true source of information is at the same time decentralized (original data) and centralized (new meta-data) and the corresponding connections would then be categorized as bidirectional.

Both roles have advantages and disadvantages regarding the implementation of SD-planning tools. While the **meta-data** approach offers a high integration of sustainable parameters into the data-model by using them as the basis for further procession, it may also generate defective inference and cause errors and dissent when returned to the original data-pools. Furthermore, these errors may cause extensive effort to be traced back to their origin due to their complex computation. Contrary, the **data-consolidation** approach results in easily traced back information-structures and respective deviations and errors, but lack additionally created meta-data which is potentially be used to gain a strategic edge for the company.

To develop the meta-data approach even further, the task of managing the data in the warehouse and create new insights can be outsourced, when the database is offering third-party-controls. This concept is depicted in Figure 47. In this concept, the data is retrieved from the data warehouse, saved and manipulated in the data handling tool and again pushed back to the data-warehouse. As for all modularization approaches, the use of these as external control tools may increase the initial effort to set up the IT environment due to more interfaces and may decrease the overall cost for licenses due to a higher range of useable warehouse solutions.

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[16] New insights can be created by using analytical algorithms or machine learning methods. Summarized as “Data Science”, the creation of new meta-information out of large heterogenous databases gained increasing attention and economic effect in recent years (Schabenberger,(2019).

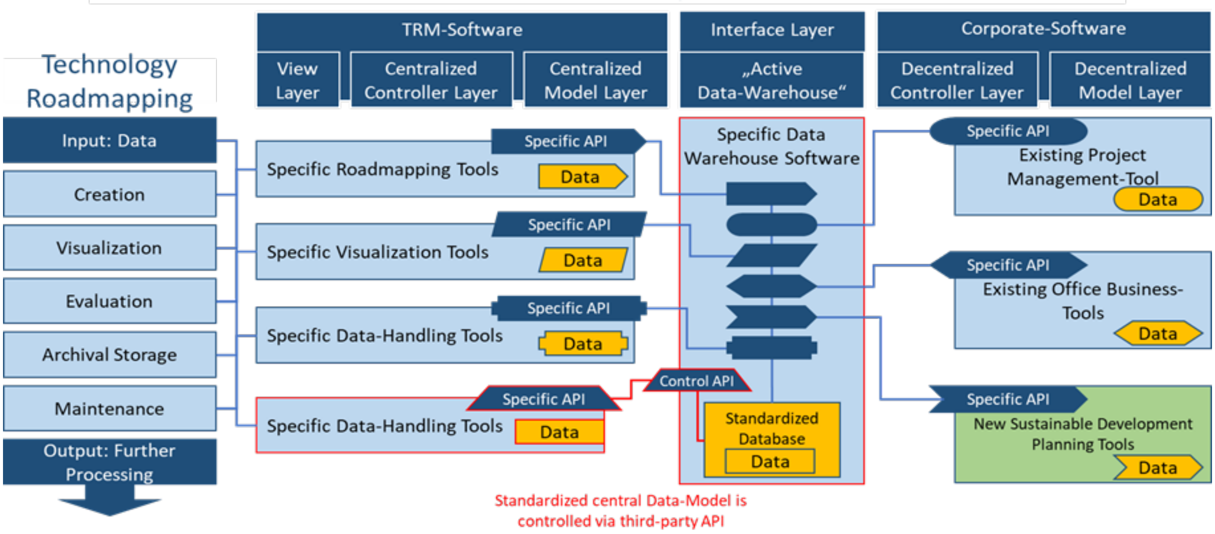

Figure 47 IT framework with centralized data-preparation and a third-party application as a controller (Source: personal collection)

As described by the example of Sharpcloud in section 3.1.3, there are tools that are specifically designed to manage and visualize data, modify dependencies and create inference out of them. This approach might be especially appealing for the integration of SD in smaller companies, as there are data-manipulation and visualization possibilities that are normally only found within enterprise-level warehouse tools.

Another advantage of the meta-data approach is the possible integration of **open-innovation concepts** into technology roadmapping. By creating meta-data that does not allow to draw conclusions about the original data, internal corporate secrets are kept within the corporate tools, while the meta-data may be shared with external partners. As a result, the complex integration of sustainable aspects into technology roadmapping may be greatly facilitated by the scalability and transparency of open-innovation with, at the same time, incorporated protection of specific business secrets. Further advancing the architecture, failsafe redundancy and cross-checking of inference by different tools is made possible with the least effort comparing to the other approaches in section 3.3, as data-connections can be simply duplicated to more than one warehouse or software-tool (see Figure 49).

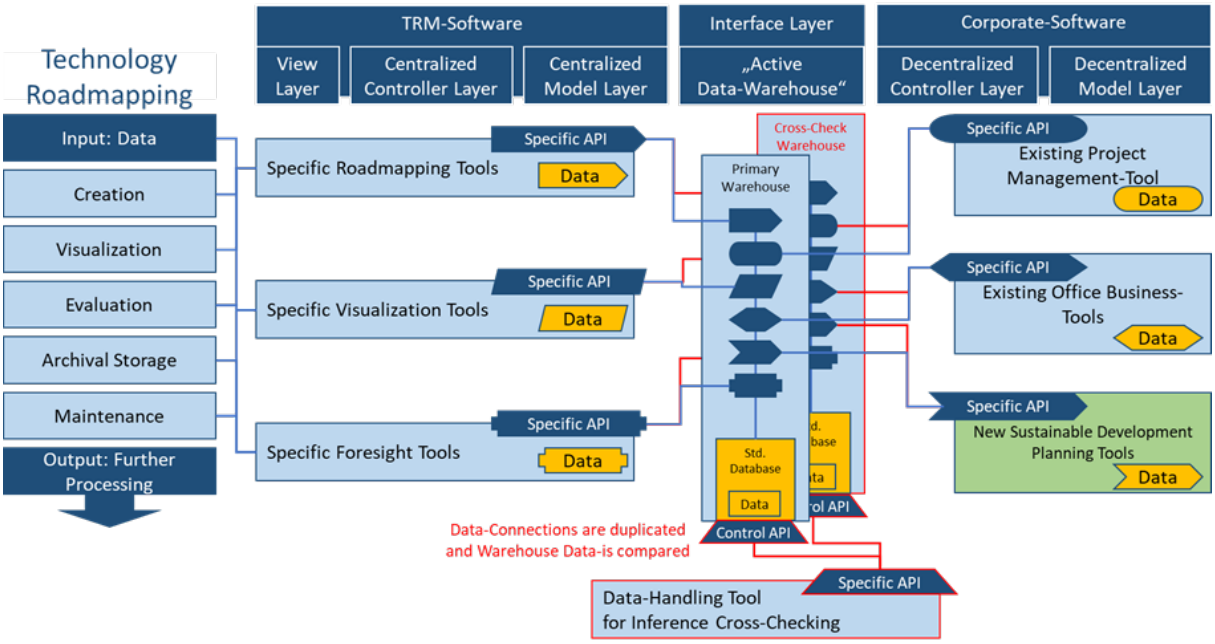

Figure 48 Enhanced IT framework with centralized data-preparation and inference cross-checks (Source: personal collection)

This is getting especially important with bi-directional communication between tools when it comes to the aforementioned generation of meta-data, as reliable error-prevention and -retracing is needed for a stable operation-mode of the whole concept. Additionally, the security of the IT environment is enhanced, as data-integrity of a single warehouse is checked against a second warehouse.

Summarizing, the standardized and centralized data-preparation approach by using a data-warehouse in combination with TRM- and SD-tools offers the most architectural leeway of all introduced approaches. While this implies the most IT knowledge necessary for setting up and maintaining the IT environment, modularization also result in the least financial and strategic dependencies on single software companies. Another conclusion of this architectural freedom is the self-determination of the integration depth of SD-planning into technology roadmapping. By using different warehouses or data-manipulation software, ecologic data can be prepared and integrated as tantamount to existing economic and technical data.

Ultimately, this approach enables the automated consideration of sustainable KPI’s and goals in existing technology roadmapping methods as examined by the most complex TRM in section 2.2.3. and supported by Quentic in section 3.2.

3.3.3 Integration of Sustainable Development Planning Tools in a centralized Information Approach with a Single-Tool Workflow

As the most centralized approach, the use of corporate standard software, combines information- and function-centralization within a single tool as explained in section 3.1.3 by the examples of ITONICS and Accolade®. Therefore, the information preparation, standardization and manipulation are done within this so-called software suite which includes modules for all needed steps of technology roadmapping. As depicted in Figure 49, the central software suite covers the facilitation of technology roadmapping tasks and request the data from existing corporate tools. As explained in previous sections, standardized API's like REST are used along with specialized API's, like Microsoft Office implementations.

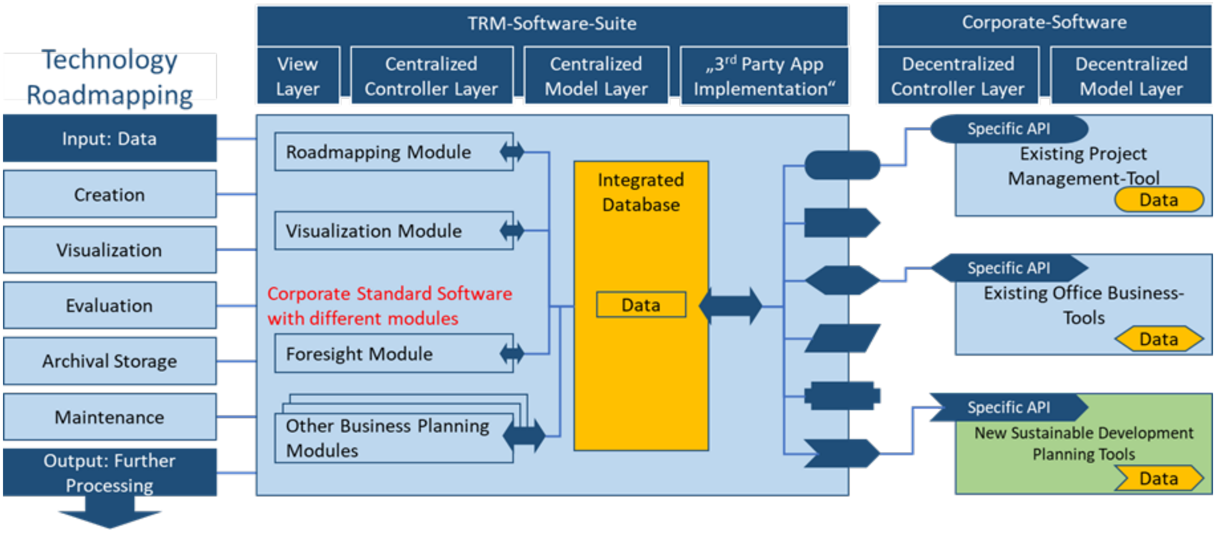

Figure 49 IT framework with a single-tool-workflow (Source: personal collection)

The implementation of SD-planning tools is dependent on the availability of suitable API's and the possibility to expand the data-model within the software suite with sustainable information. Subsequently, given the case of technology roadmapping, an implementation of SD-planning is not possible when artefacts, goals or perspectives are not able to hold any sustainable information and cannot be expanded to do so.

Though this applies to all approaches, this must be considered when choosing a certain **all-encompassing** software suite. Whereas in other approaches the certain roadmapping tools can be exchanged, the possibility to implement SD-planning into technology roadmapping is determined with the choice of the software suite and its corresponding data-model standardization from the beginning.[17]

This implication of limited architectural freedom was identified as a problem by several companies, including Sopheon (see section 3.1.3), which resulted in a possible variation of the positioning of the software suite within the given corporate IT environment. With a variable information exchange as explained by Accolade® in section 3.1.3, the role of a software suite

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[17] As an exception from this statement, large companies are able to comission an adaption of even software suites to their needs. However, the investment and maintenance costs for this option are out of all proportion to the aforementioned approaches.

as an enhanced data-warehouse with additional business planning possibilities is made possible. By the case of technology roadmapping, a software suite that is controlled by a bi-directional data-exchange of external technology roadmapping tools is depicted in Figure 50.

As depicted above, the given tools can be defined as exchangeable modules of an IT environment which makes this approach a **hybrid solution** of a centralized data-warehouse (see section 3.3.2) and a centralized software suite.

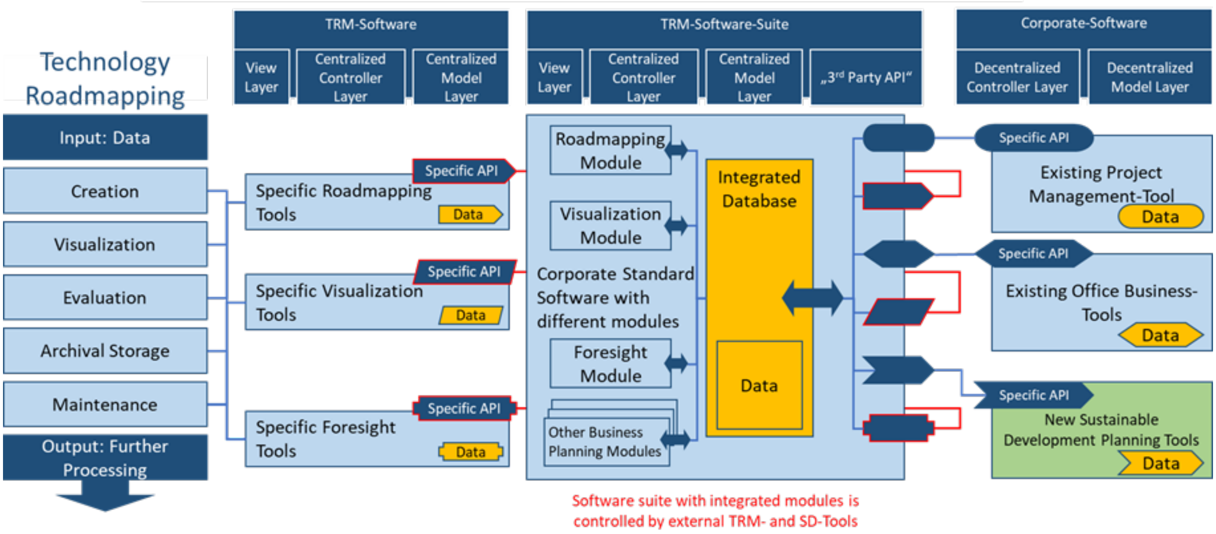

Figure 50 IT framework with a centralized bi-directional software suite (Source: personal collection)

While carrying over the advantages of a centralized warehouse, this approach as well includes the additional business planning modules of the chosen software suite and therefore facilitates the integration of additional business planning tasks within the technology roadmapping activities (f.e. decision workflows of higher management and scouting). Out of a functional perspective, this hybrid approach is the most extensive of the examined ones in this section. On the downside of this hybrid approach, the tool redundancy[18] is paid with the highest license costs as the existing tools as well as the software suite has to be acquired.

Summarizing, a centralized single-tool workflow by implementing a software-suite enables a quick-start to an all-encompassing technology roadmapping approach, if the chosen suite covers the needed modules. As interaction between modules and the integrated data-warehouse is already set-up by the product itself, the least IT knowledge is needed for a simple implementation into a given corporate IT environment. Beside the general set-up effort of a new IT tool, this approach might necessitate data-migrations from existing software-tools, if their tasks are now taken over by the software suite. Regarding the implementation of SD-planning into the

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[18] However, tool redundancy can be intended for data-integrity and -validation puposes as explained in section 3.3.2.

process of technology roadmapping, several conditions must be checked and met while choosing the software-suite. This includes the direction of information flow (mono- or bi-directional) to enable an interaction of the suite and SD-planning tools and the possibility to expand given data-models of artefacts, goals and perspectives with sustainable data. Exceptions from this can only be accepted, if the suite is implemented in a hybrid-approach as an enhanced data-warehouse. As already explained in previous sections, any functional centralization based on bought software-tools result in a dependency to that software-supplier.

3.4 Review and Evaluation on how to integrate Sustainability in Technology Roadmapping by IT

In section 3, the synopsis of existing software tools facilitating technology roadmapping and another for SD-planning tools were used to examine different approaches of integrating both into an IT environment. These approaches are now critically compared regarding the research question and regarding their applicability into an existing IT environment of a company. To do this, a simplified diagram is used to depict the architectural steps within the approaches of the previous sections (see Figure 51).

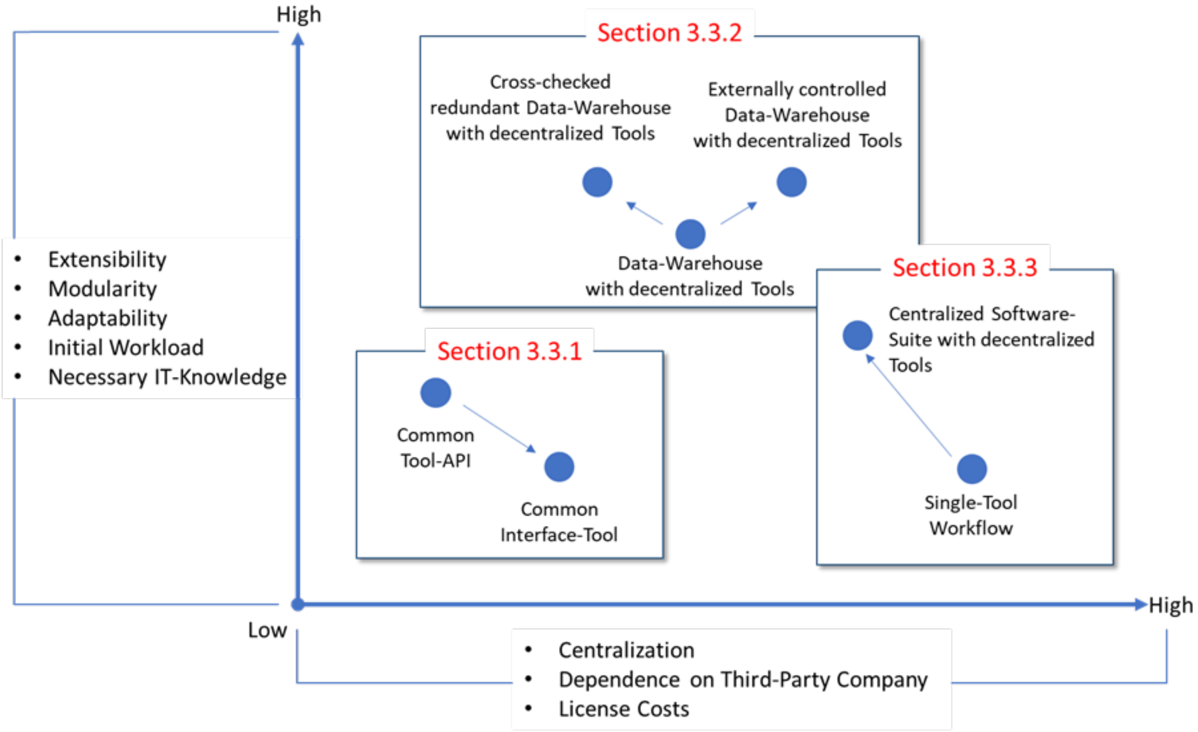

Figure 51 Comparison of IT Framework approaches (Source: personal collection)

Starting with section 3.3.1, two approaches were explained in which the information is held in decentralized tools and their corresponding data-storage. While either the tools are chosen to have a common API or a third-party application is used to connect tools, the adaptability and architectural freedom is limited as well as the possible automation of the whole process. This is reasoned by the combined information and functional decentralisation which makes a superordinate control by means of an integrated technology roadmapping difficult to realize. Speaking of the facilitation potential for integrating sustainability aspects into technology roadmapping, this approach works for IT environments with few systems and tools, as the integration effort rises exponentially with every new tool and perspective within technology roadmapping.

To avoid this exponential rise of complexity, a centralized information data-warehouse is needed. In this context, with every new tool in the framework, a single tool-warehouse connection is established. The tool will request and respond data from or to the warehouse and vice-versa, without having to know the originate application interface of other tools that as well give input into the warehouse.

This approach can be separated into a more generalized data-warehouse with separated technology roadmapping tools, which is examined in section 3.3.2, or into a more specialized software-suite with integrated technology roadmapping tools, which is examined in section 3.3.3. In either way, the integration of SD-planning tools is realized via pre-defined API's and controlled internally within the data-warehouse or externally via third-party applications.

Comparing all approaches, the result of the literature research in section 2.2.3 is replicated: with rising modularity, adaptability and automation, a higher integration depth of sustainable aspects can be achieved in the database of technology roadmapping. With rising modularity, tasks can be separated into specialized tools, which still achieve the same information throughput as single-tool-workflows as information is automatically exchanged by API's. However, this necessitates the most IT knowledge and initial workload. Therefore, a higher position in the diagram in Figure 51 translates into a better integration depth of sustainable aspects as tantamount to the existing perspectives and targets within technology roadmapping.

Critically comparing the examined approaches, another aspect becomes evidently important in a real-life scenario: *dependency*. With either of all approaches, initial workload has to be done to set-up an integrated technology roadmapping. However, with single-tool workflows, a dependency is created with the third-party software-supplier.

To choose a full integration of an all-encompassing software-suite corresponds with an at least mid-term dependency to the pricing and maintenance of the company providing it. While modular approaches enable an iterative implementation of technology roadmapping and SD-planning tools in which mistakenly chosen tools can be rather easily exchanged for other, a late detection of a wrong tool-choice or discord with third-party choices can have much more cost-intense impact in a single-tool scenario.

Ultimately, regarding the research questions, all of the examined approaches facilitate technology roadmapping and the integration of sustainable development planning by standardizing the information base (data-model) and address the most critical success-factors and barriers of success of technology roadmapping to a different extent. This common and prevailing information base of tantamount economic and ecologic aspects is necessary to consider both to the same extend in technology roadmapping.

4 Conclusions

This thesis examined the current implementation of sustainability in technology roadmapping and approaches to facilitate this integration. It was shown by a systematic literature review, that most found technology roadmaps either focus on technology and products or sustainability, but very few did both. To extenuate exponential complexity of multiple perspectives, these few examples used algorithms and IT tools to automate complex technology roadmapping steps, which also may be applied to the complex integration of sustainable aspects.

Reasoned by these cases and general advantages of a seamless digitalized workflow, selective examples of current IT tools for technology roadmapping and sustainable development were chosen subsequently and examined by their facilitation potential regarding a technology roadmapping striving for sustainability. In the last section, these facilitation concepts were brought together in three different abstract framework approaches to highlight respective conceptual advantages and disadvantages. Again, it was shown that complexity can be handled, if applicable measures regarding the interaction and architecture of IT tools are taken with necessary IT knowledge and initial workload. If applied however, an automated integration of SD-planning tools and corresponding sustainable perspectives, goals and artefacts in technology roadmapping tools may be realized without exponential workload due to complexity of additional perspectives.

Further expanding the scope of consideration beyond this thesis’ research questions, a systematic automation and comprehensive data-model standardization within the corporate IT environment can be used to integrate other functionality into technology roadmapping. For example, the information base of technology roadmapping can be enhanced by autonomous data-seekers that search the internet for patents and technological publications. Additionally, interdependencies within TRM can be autonomously checked by neural networks that are trained on the basis of other TRM. In the same way, inference can be created by machine-learning on the basis of given interdependencies and scenario-simulation, to react on new insights of climate research.

Concluding, the integration of sustainable development planning into technology roadmapping will become more important as a part of a far-reaching integration of sustainability into every value chain in general. Based on this thesis, subsequent research may use a given approach to target fully autonomous technology roadmapping as a method to keep pace with the rapidly changing wishes and complex needs of the future generations.

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Appendix A Referenced Pictures of found Technology Roadmaps

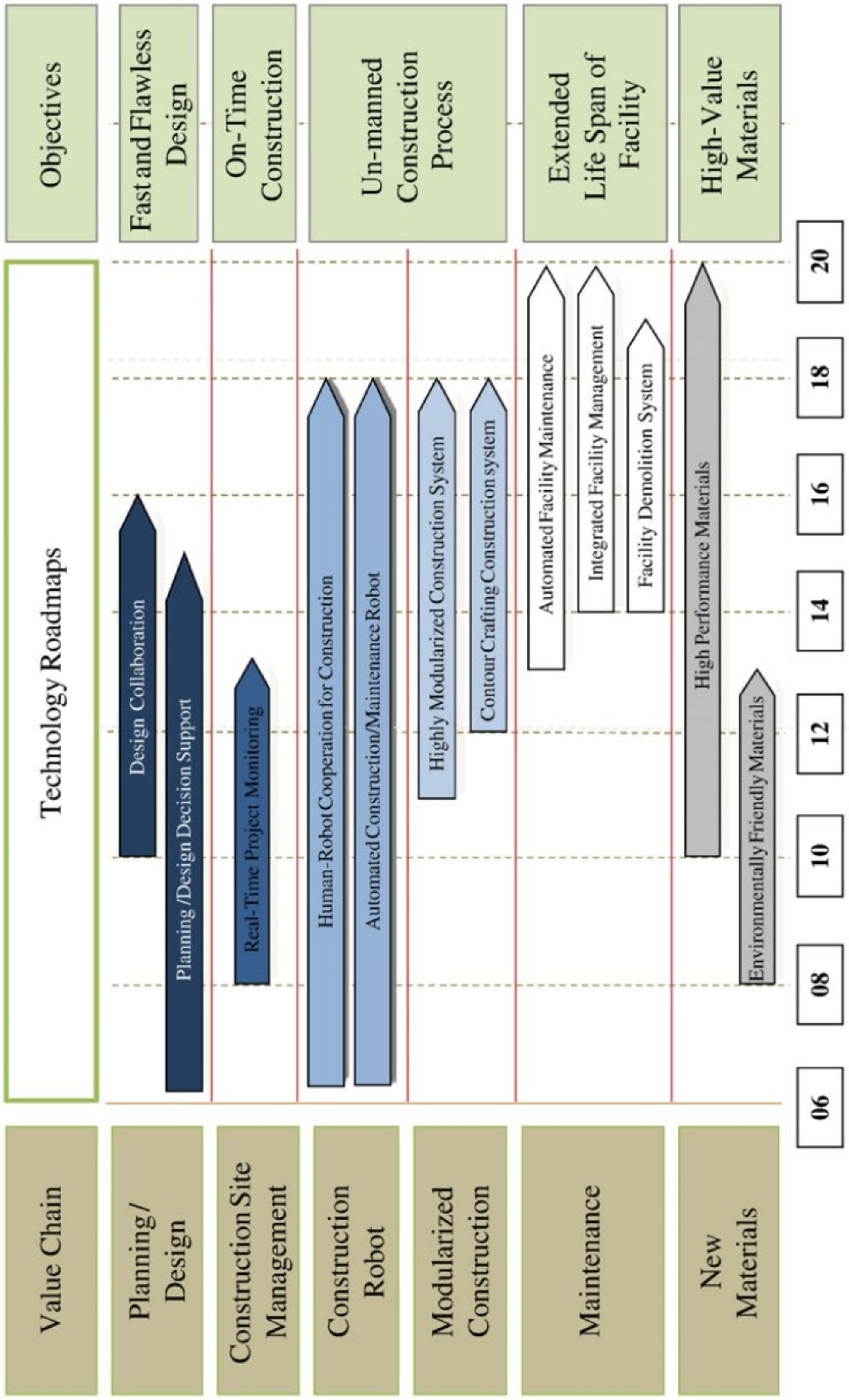


Figure 52 Technology Roadmap for construction R&D at a macro level with 12 grouped sub-technology roadmaps (Kim et al., 2009, p. 335)

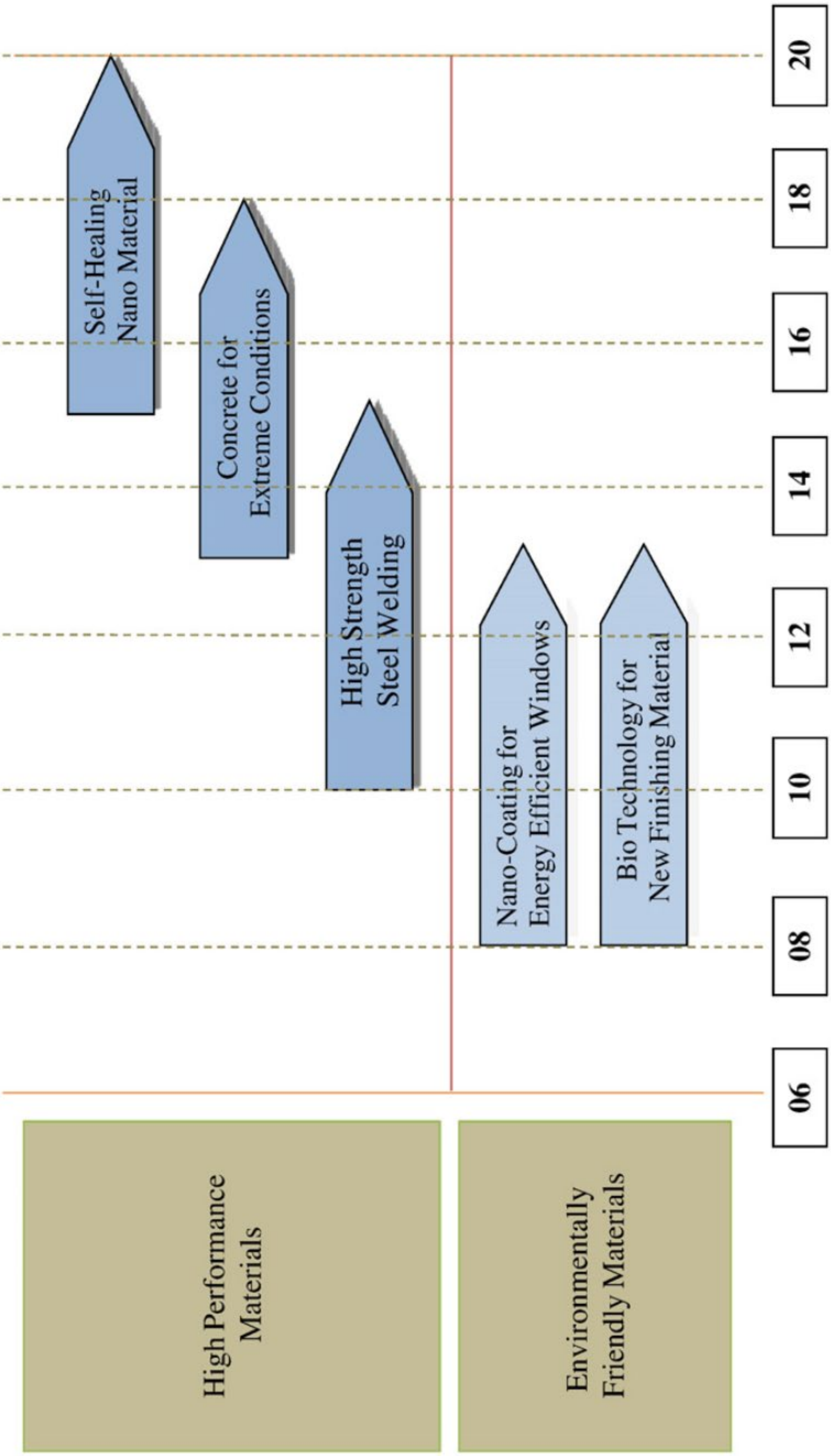


Figure 53 Sub-technology roadmap for new materials in construction with separate perspective for sustainable aspects (Kim et al., 2009, p. 335)

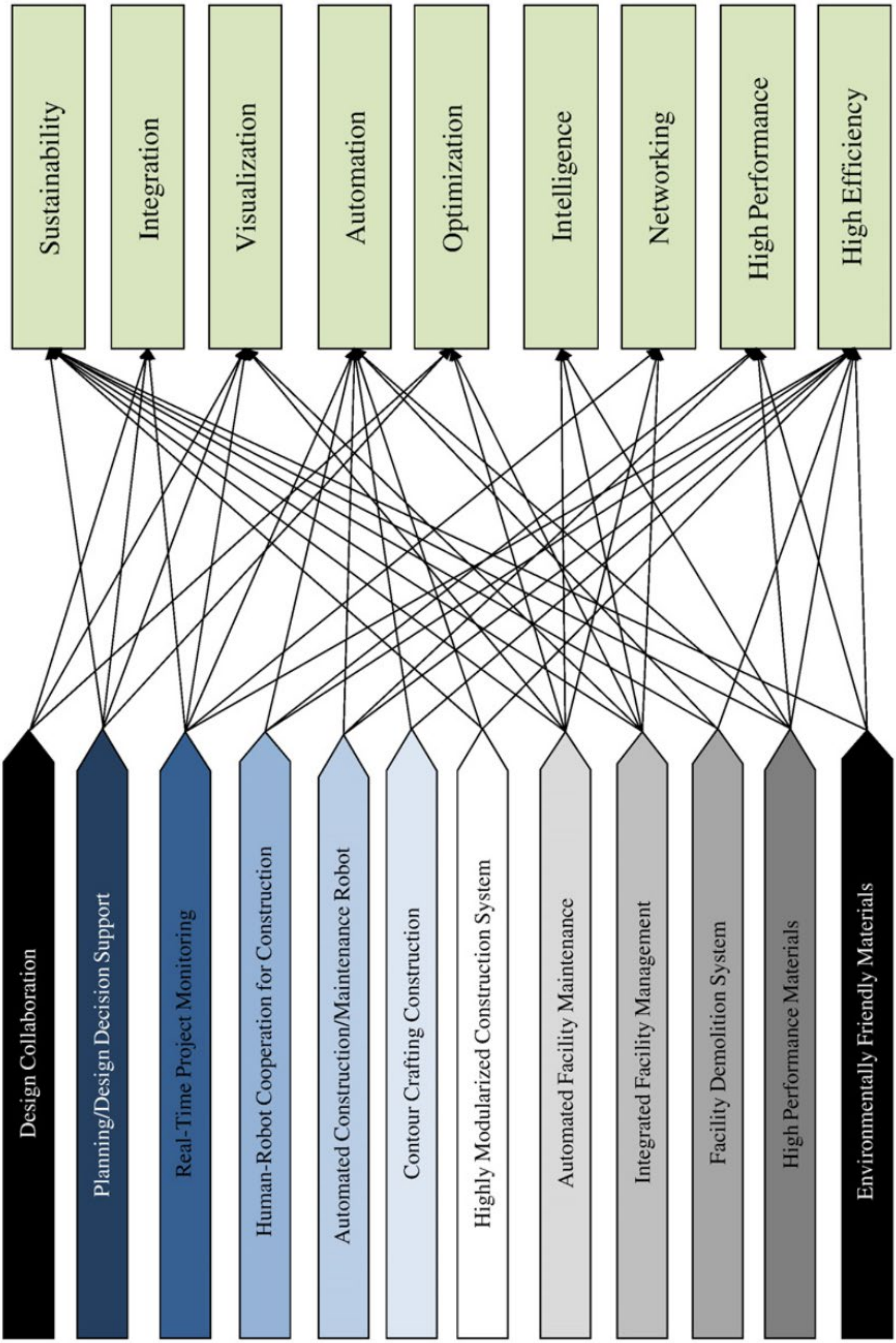


Figure 54 Assignment of sub-technology roadmaps to different research aspects, including sustainability (Kim et al., 2009, p. 336)

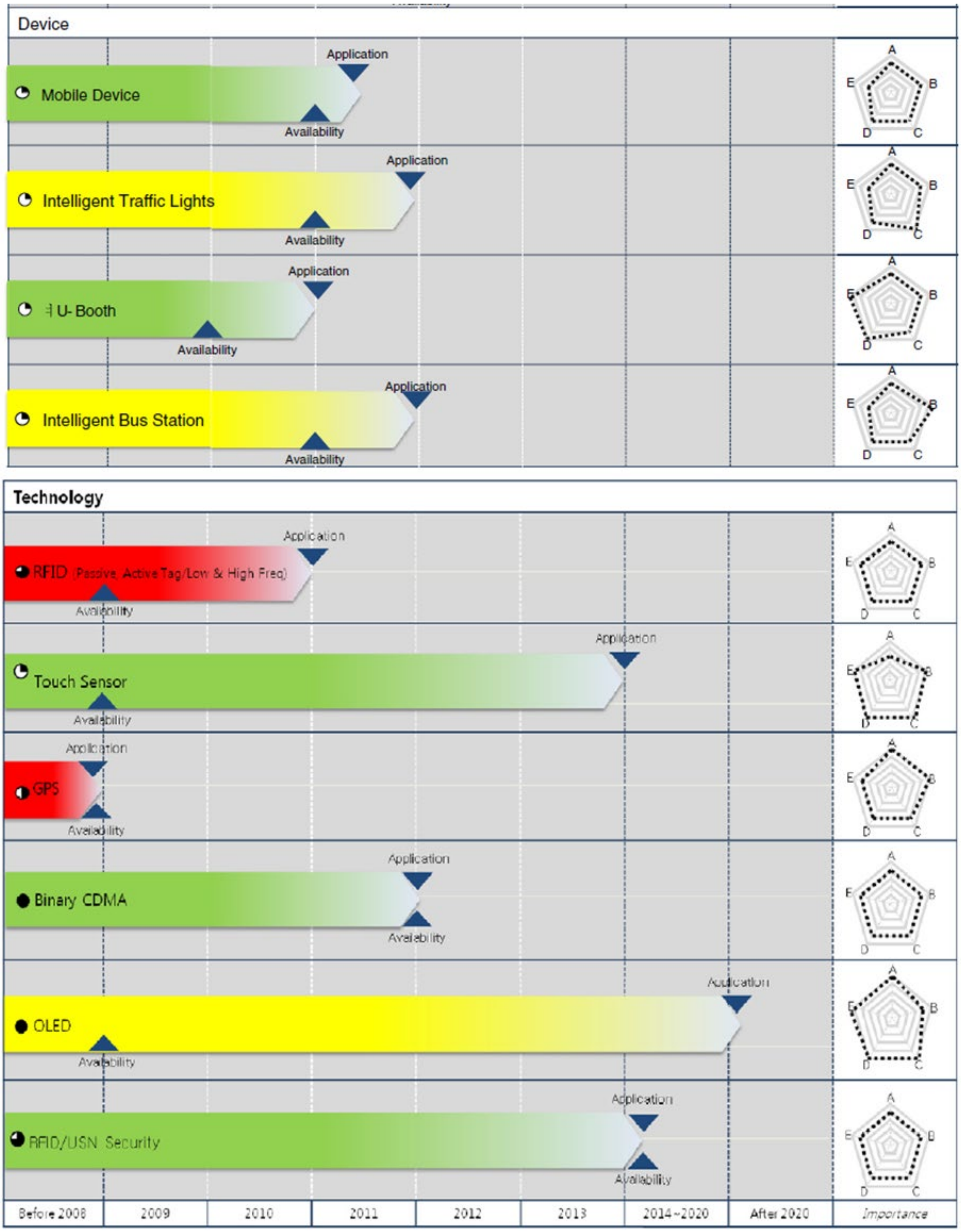


Figure 55 Technology roadmap for public transportation information services with technology artefacts (J. H. Lee, Phaal, & Lee, 2013, p. 300)

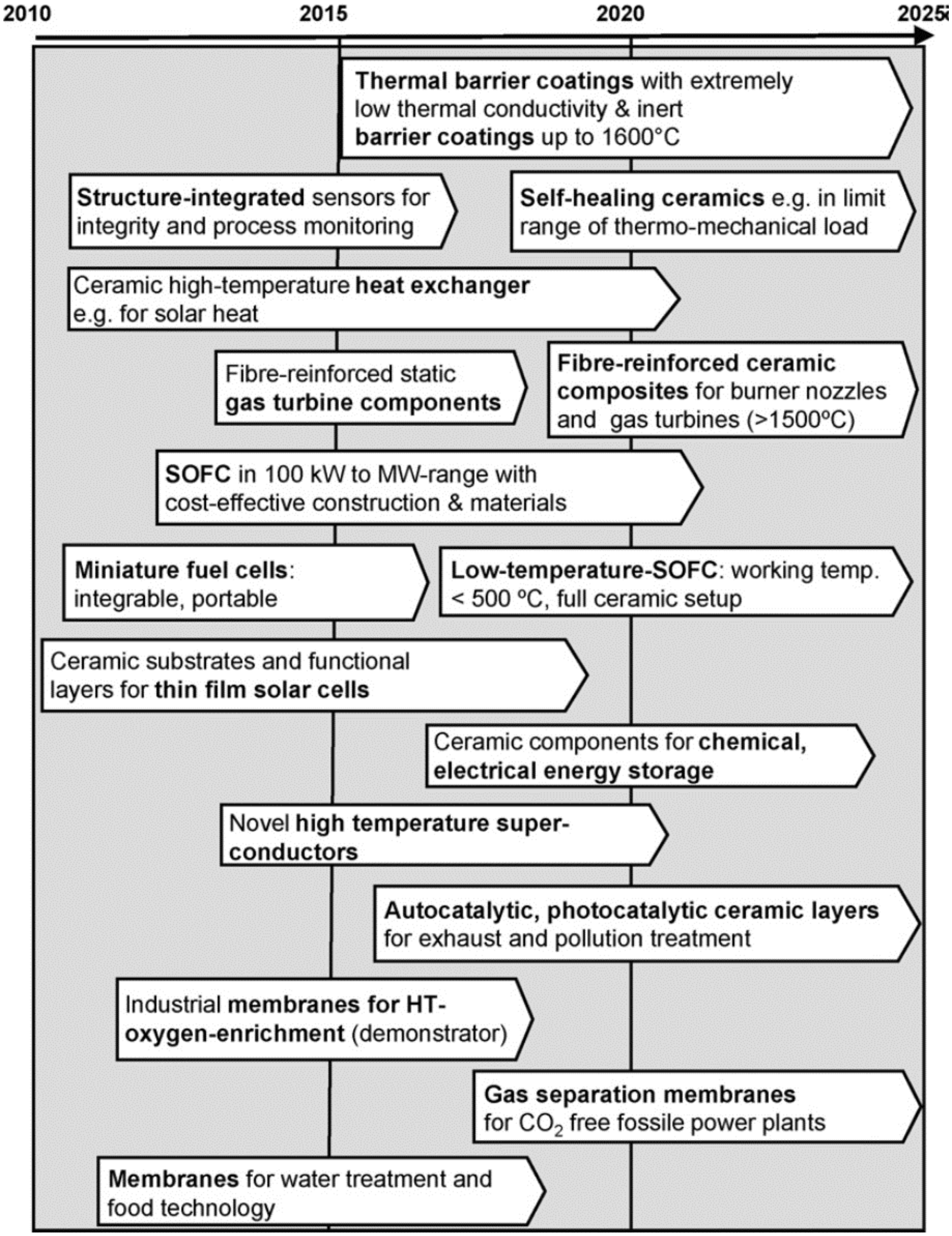


Figure 56 Roadmap for advanced ceramics with product artefacts (Rödel et al., 2009, p. 1555)

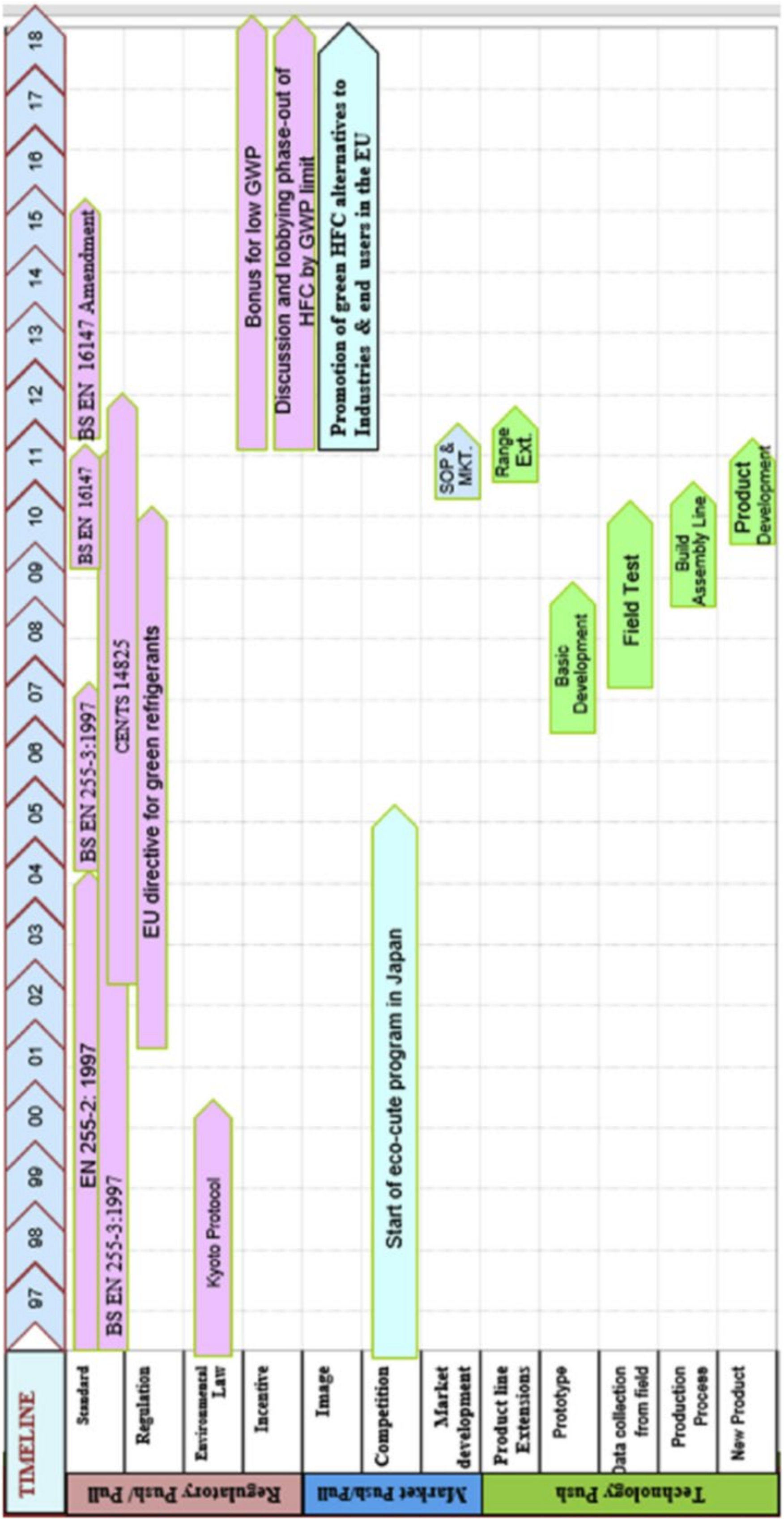


Figure 57 Technology roadmap for adoption of an eco-program in Europe with regulation and standard artefacts (Khanam & Daim, 2017, p. 166)

Figure 58 Energy-efficiency roadmap for Uganda with goal artefacts (La Rue Can, Pudleiner, & Pielli, 2018, p. 362)

	2015	2020	2025	2030
Bioethanol	Start increasing quota mandates	Achieve E15	Achieve E20	Implement E85
Biodiesel	Start increasing quota mandates	Achieve B20	Achieve B25	Achieve B30
Renewable diesel	Start producing	Achieve 4% contribution	Achieve 7% contribution	Achieve 10%
Biomethane	Start producing	Use 1.5% biomass residues and 0.3% animal waste	Use 3.5% biomass residues and 0.6% animal waste	Use 5% residual biomass and 1% animal waste
Power generation and CHP	Start renewable target and exploitation of biogas/landfill gas	Achieve 3% renewable target and 1/3 of goals for biogas/landfill gas	Achieve 7% renewable target and 2/3 of goals for biogas/landfill gas	Achieve 10% renewable target and 100% goals for biogas/landfill gas

Figure 59 Sub-roadmap for bioenergy exploitation with explicitly described goal-artefacts (Gonzalez-Salazar et al., 2016, p. 344)

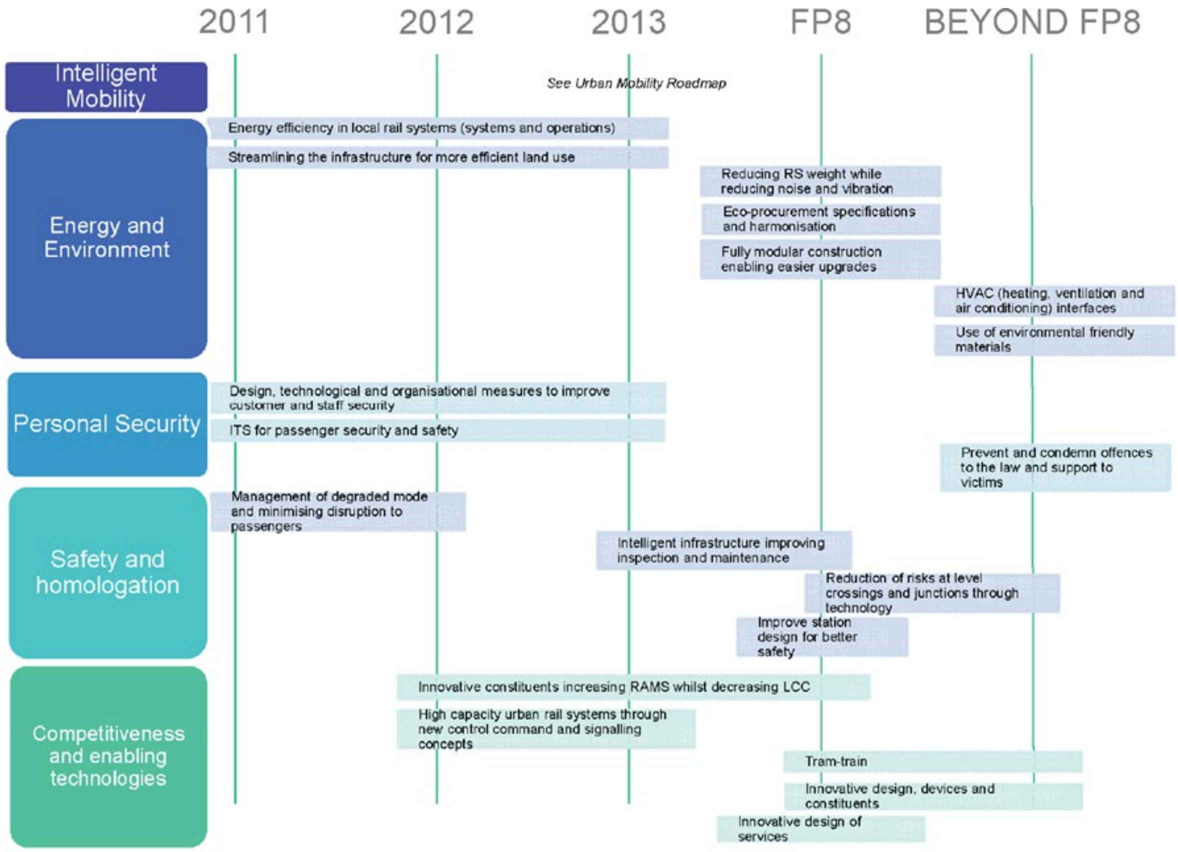


Figure 60 Technology roadmap for rail and urban mobility with implicit artefact descriptions (Hoogendoorn & Amsler, 2012, p. 2290)

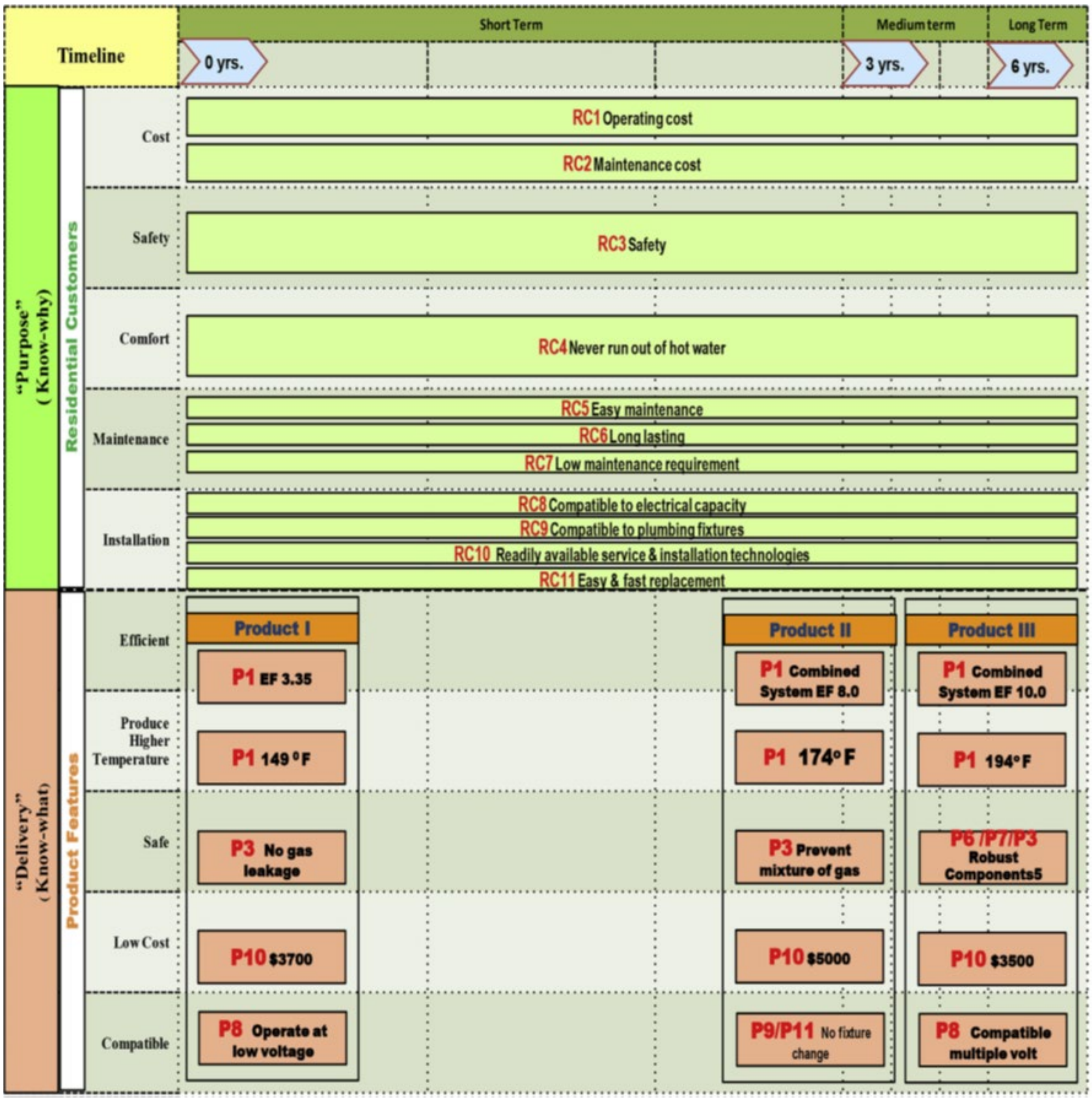


Figure 61 Part of a technology roadmap for CO2 heat-pump water-heater with explicit product descriptions (Khanam & Daim, 2017, p. 171)

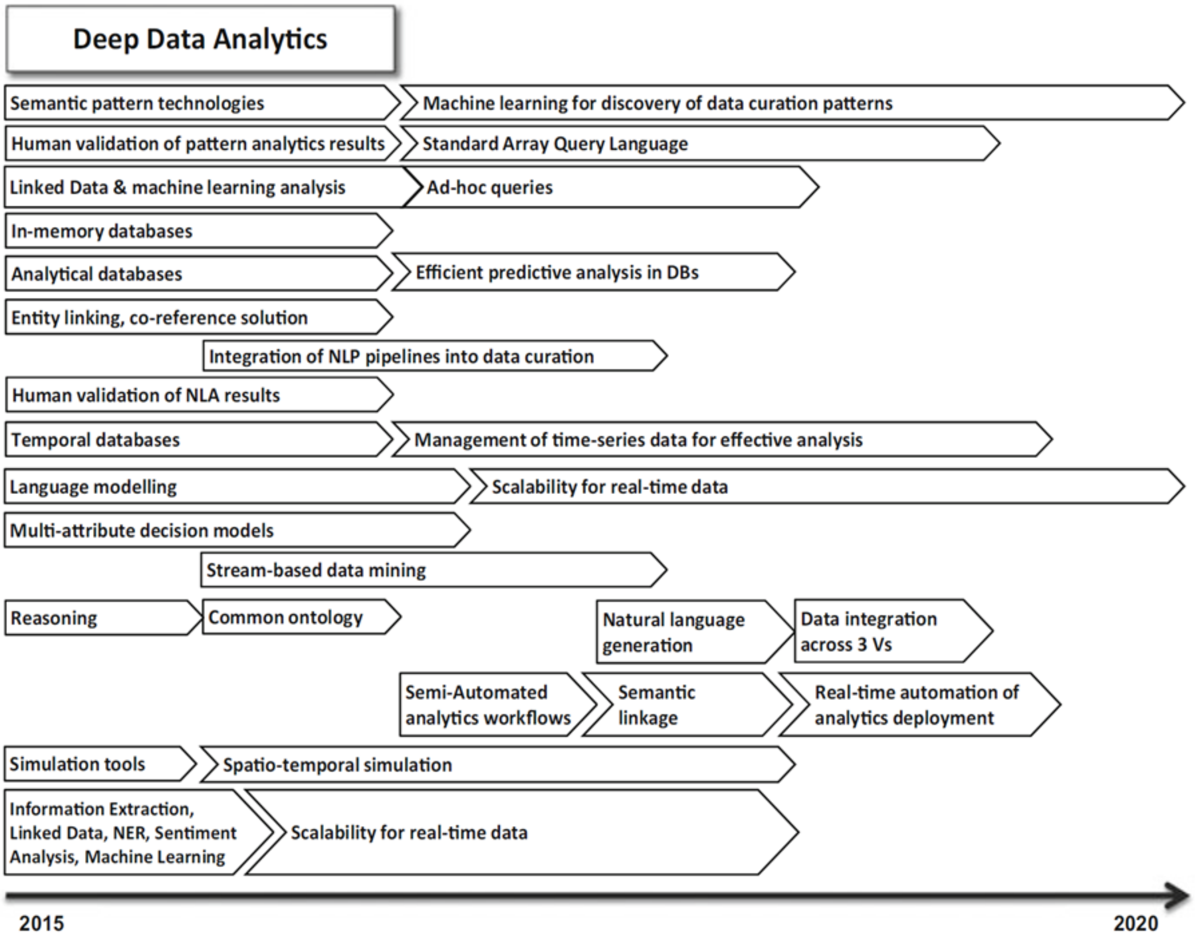


Figure 62 Deep Data Analytics" sub-technology roadmap for big-data (Cavanillas, Curry, & Wahlster, 2016, p. 280)

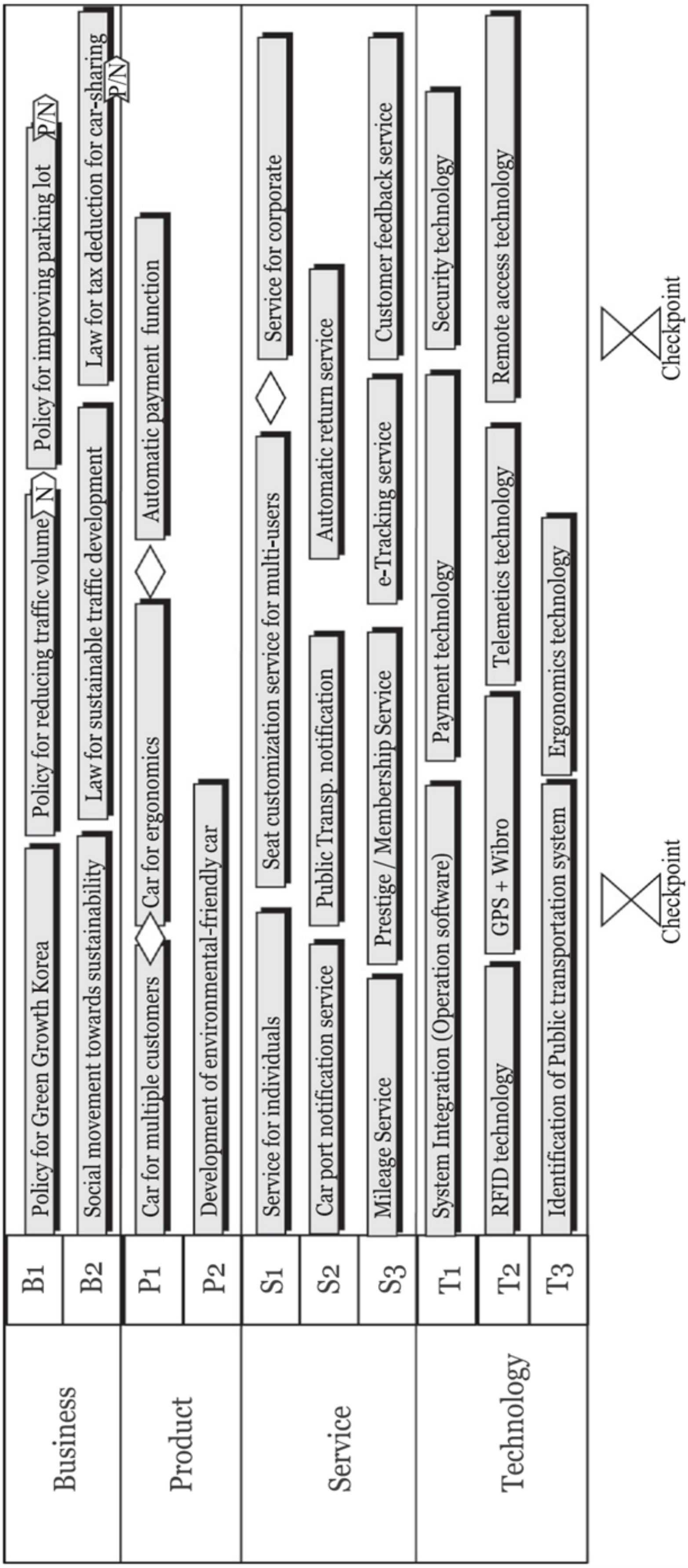


Figure 63 Car sharing technology roadmap (Geum et al., 2014, p. 44)

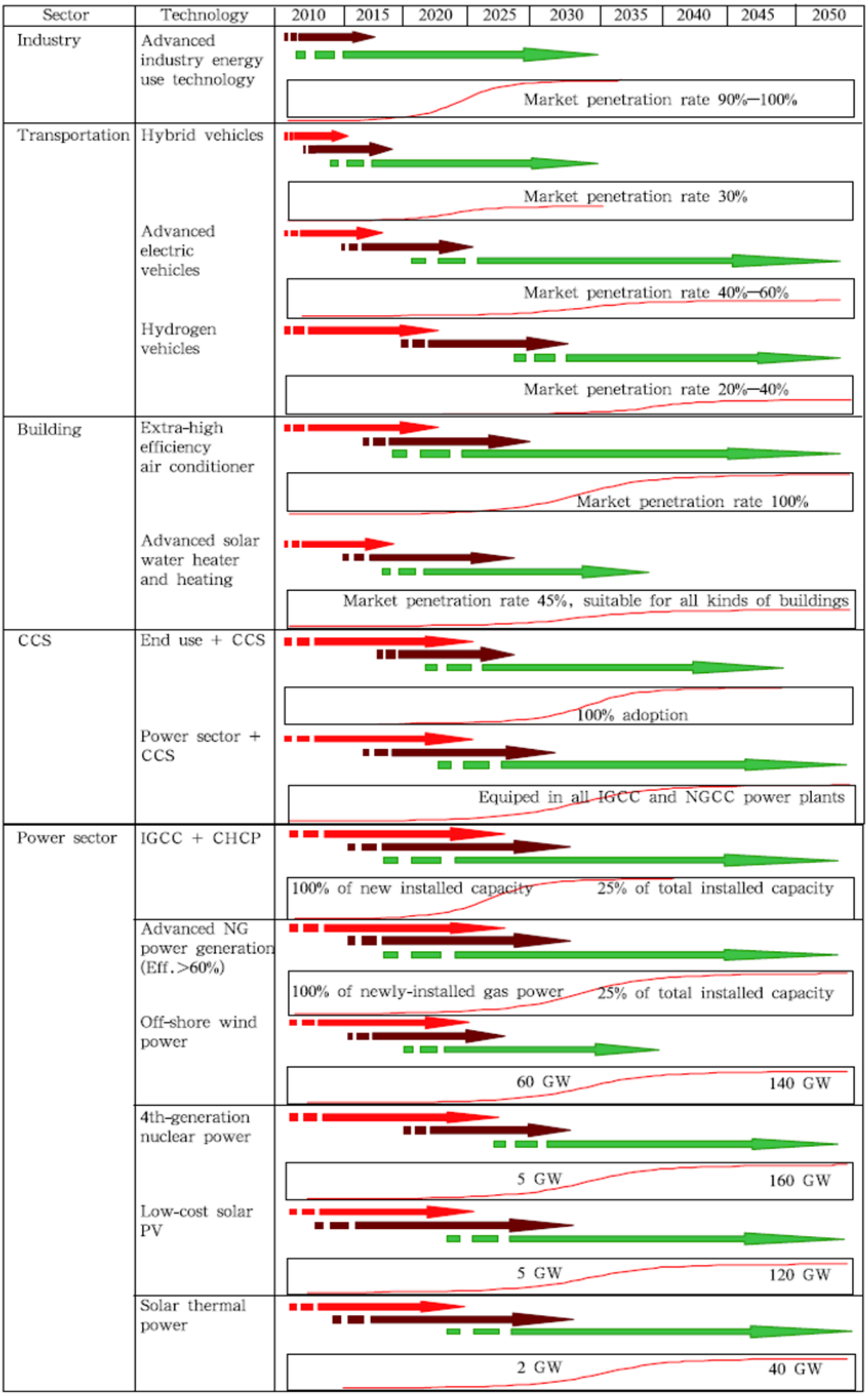


Figure 64 Technology roadmap for lower carbon emissions in china (Liu, Jiang, & Hu, 2011, p. 72)

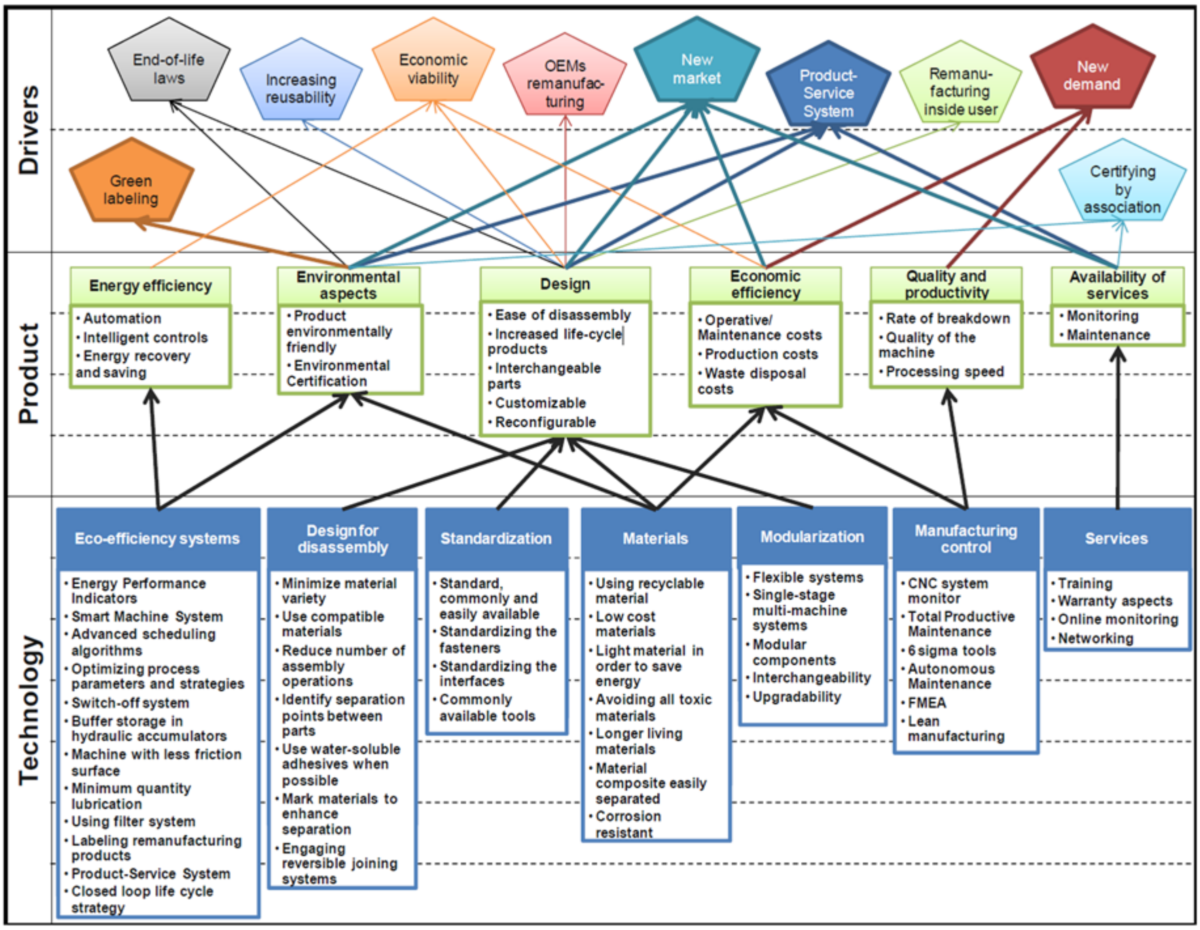


Figure 65 Technology roadmap for remanufacturing oriented production equipment (Seliger, Khraisheh, & Jawahir, 2011, p. 205)

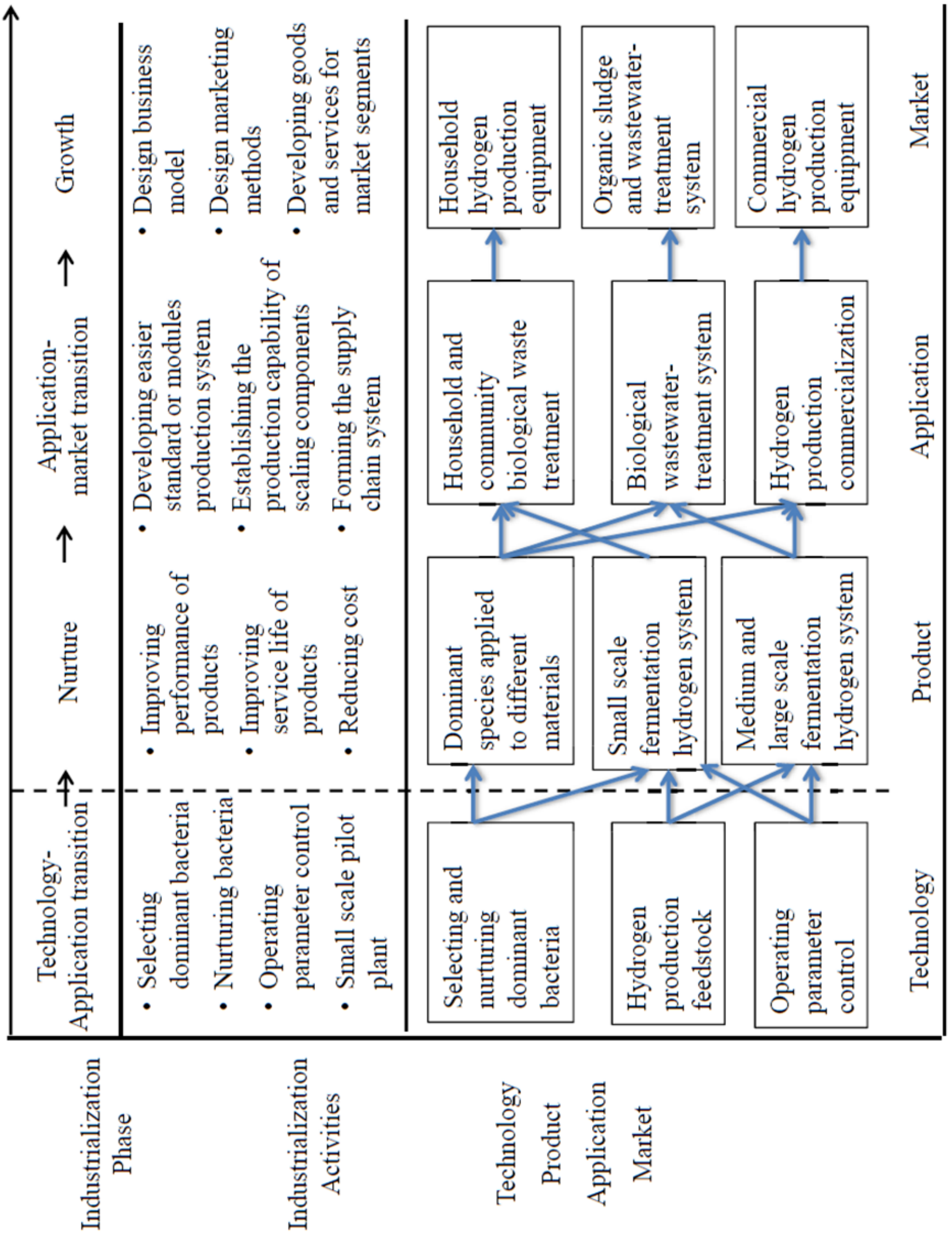
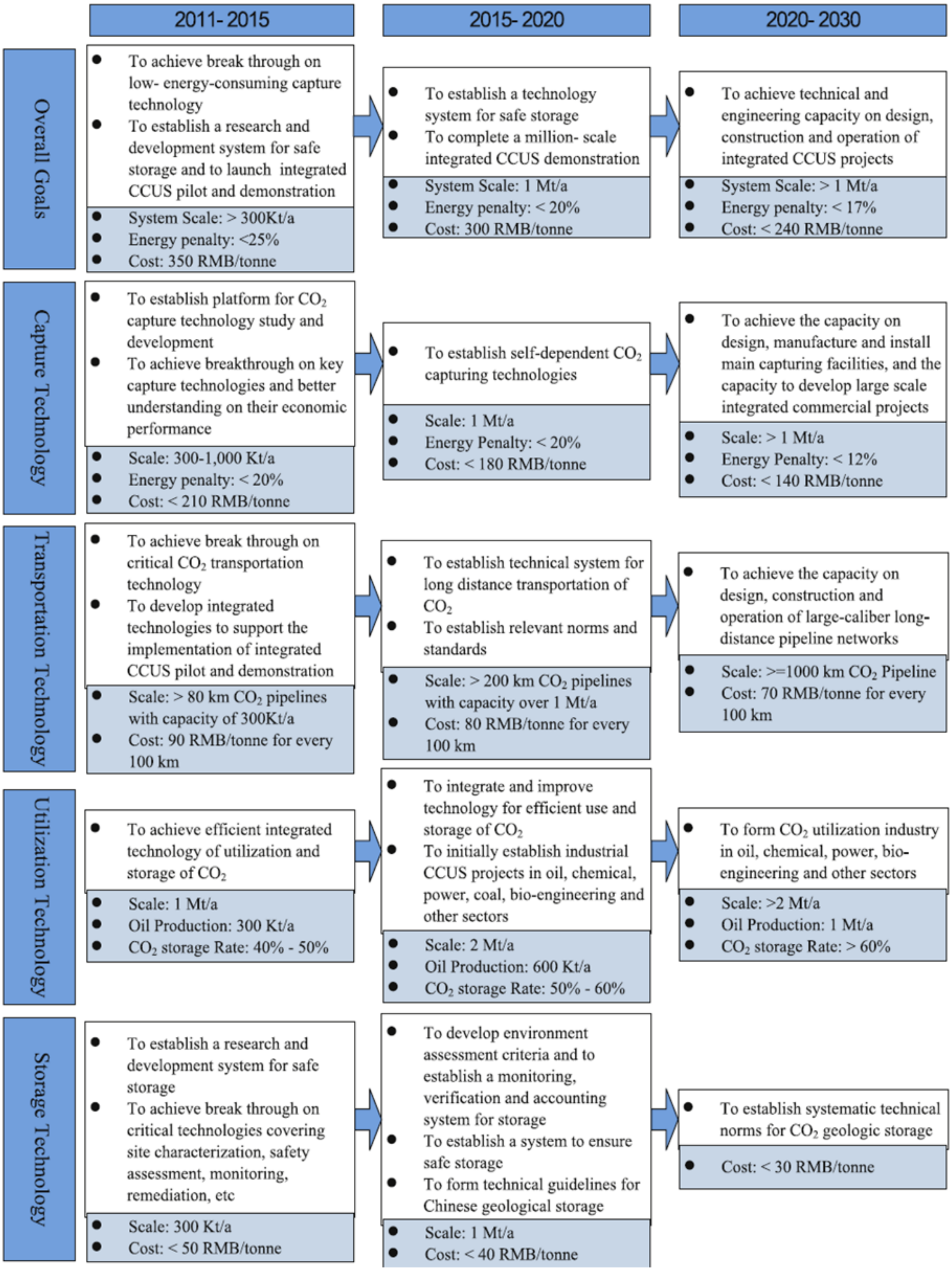


Figure 66 Roadmap for fermentative hydrogen production from biomass in Taiwan (Hsu, Tung, & Lin, 2017, p. 27468)



	2011- 2015	2015- 2020	2020- 2030
Overall Goals	● To achieve break through on low- energy-consuming capture technology ● To establish a research and development system for safe storage and to launch integrated CCUS pilot and demonstration ● System Scale: > 300Kt/a ● Energy penalty: <25% ● Cost: 350 RMB/tonne	● To establish a technology system for safe storage ● To complete a million- scale integrated CCUS demonstration ● System Scale: 1 Mt/a ● Energy penalty: < 20% ● Cost: 300 RMB/tonne	● To achieve technical and engineering capacity on design, construction and operation of integrated CCUS projects ● System Scale: > 1 Mt/a ● Energy penalty: < 17% ● Cost: < 240 RMB/tonne
Capture Technology	● To establish platform for CO_2 capture technology study and development ● To achieve breakthrough on key capture technologies and better understanding on their economic performance ● Scale: 300-1,000 Kt/a ● Energy penalty: < 20% ● Cost: < 210 RMB/tonne	● To establish self-dependent CO_2 capturing technologies ● Scale: 1 Mt/a ● Energy Penalty: < 20% ● Cost: < 180 RMB/tonne	● To achieve the capacity on design, manufacture and install main capturing facilities, and the capacity to develop large scale integrated commercial projects ● Scale: > 1 Mt/a ● Energy Penalty: < 12% ● Cost: < 140 RMB/tonne
Transportation Technology	● To achieve break through on critical CO_2 transportation technology ● To develop integrated technologies to support the implementation of integrated CCUS pilot and demonstration ● Scale: > 80 km CO_2 pipelines with capacity of 300Kt/a ● Cost: 90 RMB/tonne for every 100 km	● To establish technical system for long distance transportation of CO_2 ● To establish relevant norms and standards ● Scale: > 200 km CO_2 pipelines with capacity over 1 Mt/a ● Cost: 80 RMB/tonne for every 100 km	● To achieve the capacity on design, construction and operation of large-caliber long-distance pipeline networks ● Scale: >=1000 km CO_2 Pipeline ● Cost: 70 RMB/tonne for every 100 km
Utilization Technology	● To achieve efficient integrated technology of utilization and storage of CO_2 ● Scale: 1 Mt/a ● Oil Production: 300 Kt/a ● CO_2 storage Rate: 40% - 50%	● To integrate and improve technology for efficient use and storage of CO_2 ● To initially establish industrial CCUS projects in oil, chemical, power, coal, bio-engineering and other sectors ● Scale: 2 Mt/a ● Oil Production: 600 Kt/a ● CO_2 storage Rate: 50% - 60%	● To form CO_2 utilization industry in oil, chemical, power, bio-engineering and other sectors ● Scale: >2 Mt/a ● Oil Production: 1 Mt/a ● CO_2 storage Rate: > 60%
Storage Technology	● To establish a research and development system for safe storage ● To achieve break through on critical technologies covering site characterization, safety assessment, monitoring, remediation, etc ● Scale: 300 Kt/a ● Cost: < 50 RMB/tonne	● To develop environment assessment criteria and to establish a monitoring, verification and accounting system for storage ● To establish a system to ensure safe storage ● To form technical guidelines for Chinese geological storage ● Scale: 1 Mt/a ● Cost: < 40 RMB/tonne	● To establish systematic technical norms for CO_2 geologic storage ● Cost: < 30 RMB/tonne

Figure 67 Carbon capture technology roadmap（X. Zhang, Fan, & Wei, 2013, p. 540）

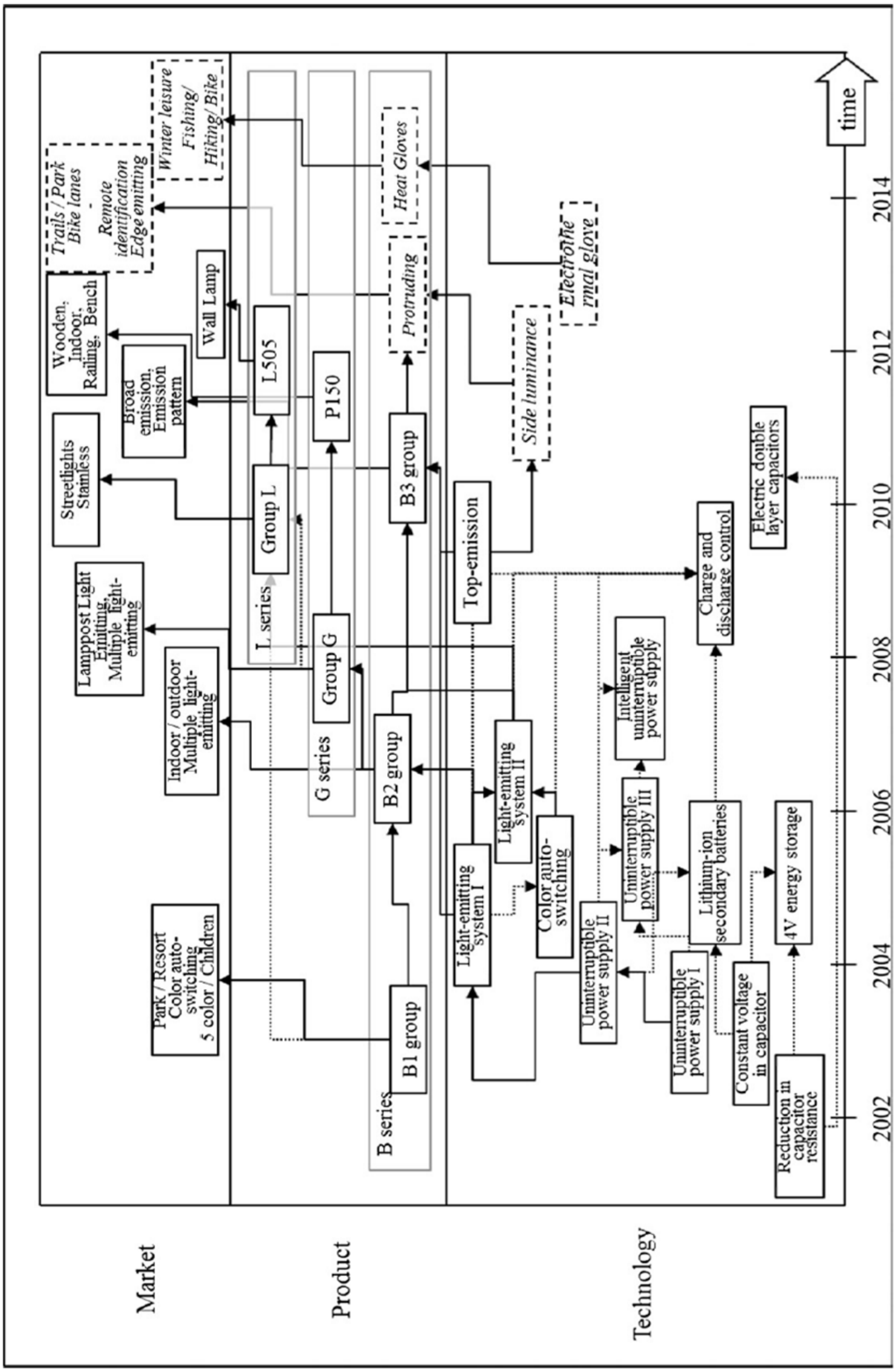


Figure 68 Generated technology roadmap of solar lightning technology (Jin et al., 2015, p. 136)

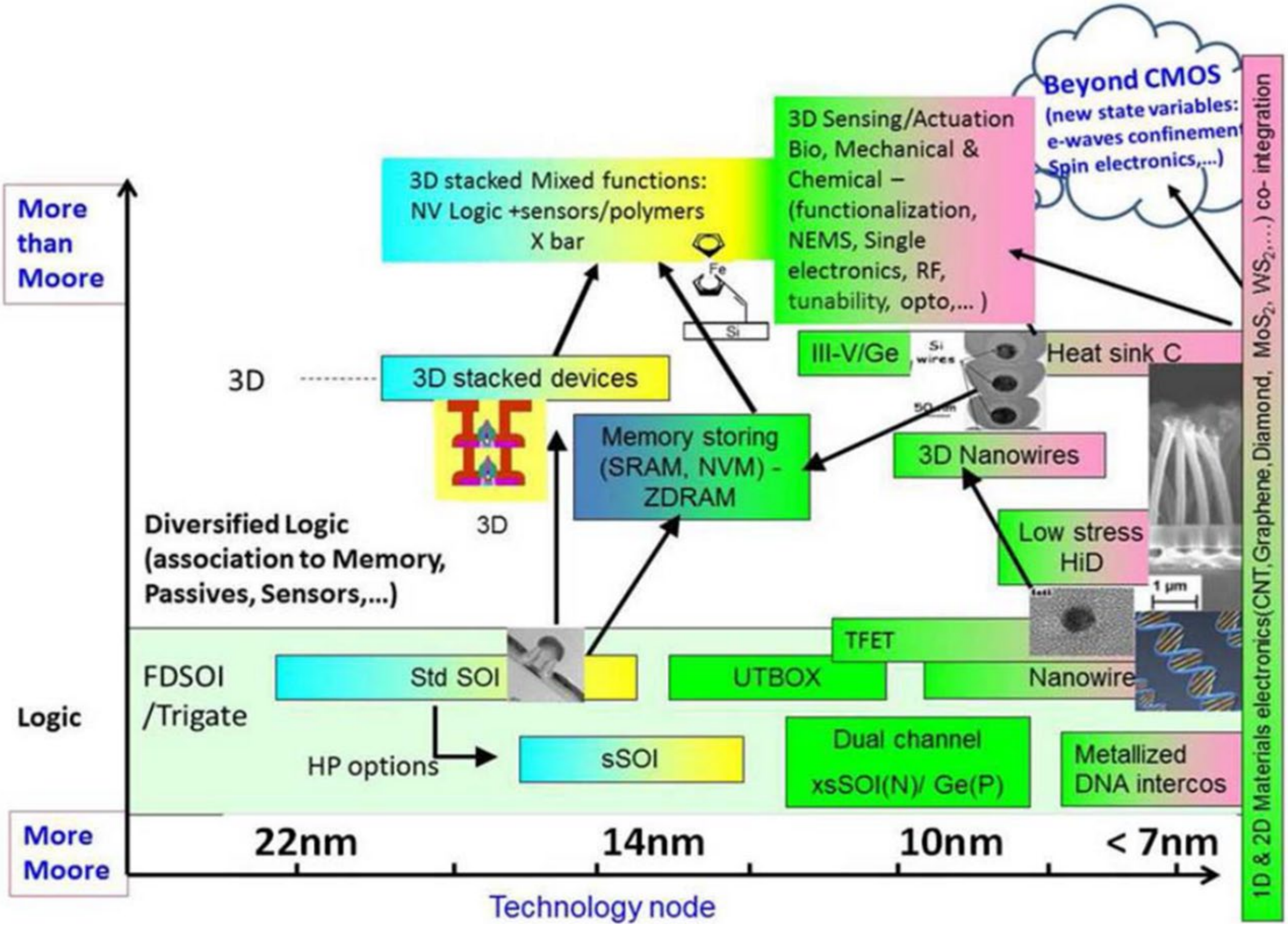


Figure 69 Technology roadmap for CMOS devices (Deleonibus, 2016, p. 243)

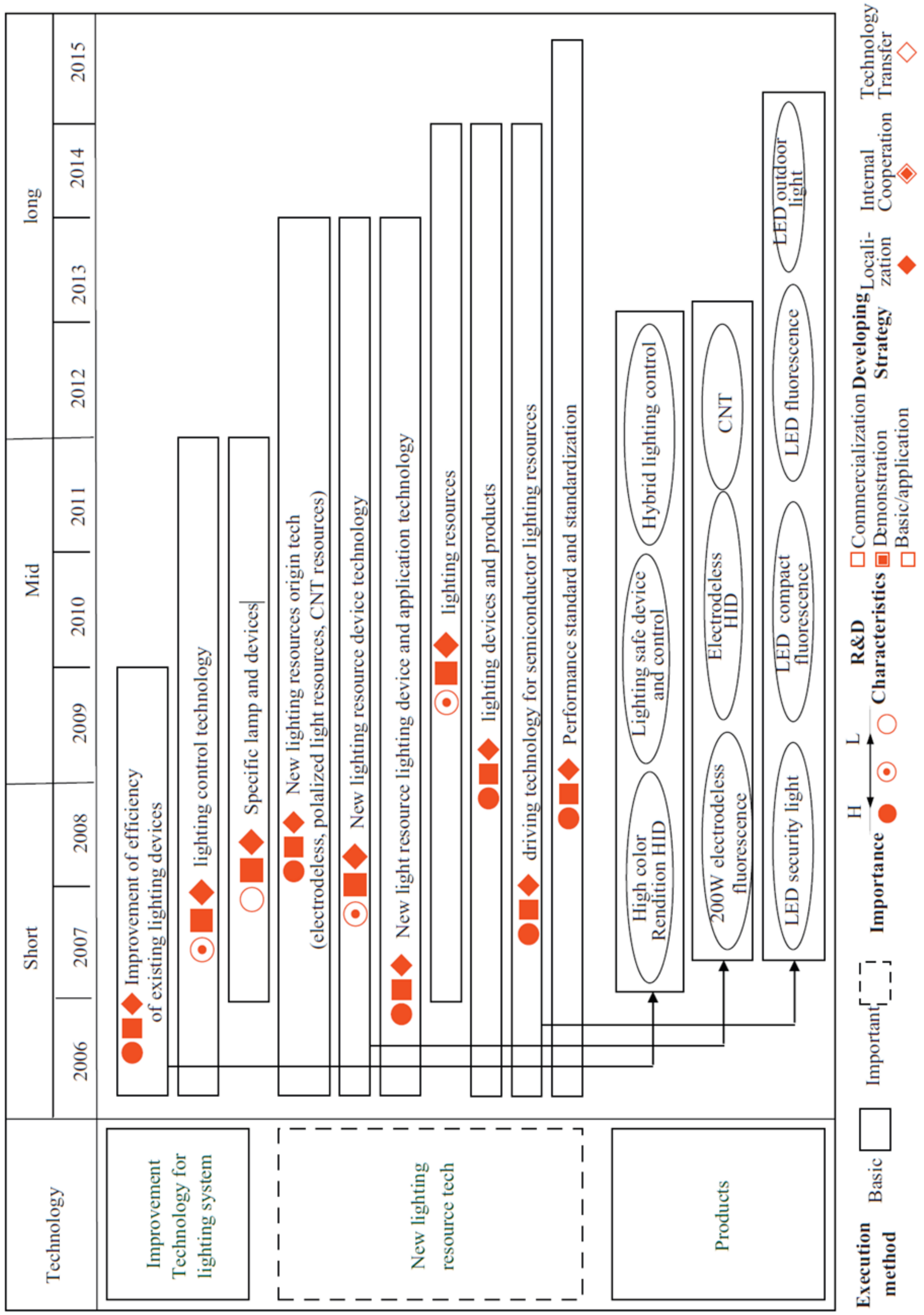


Figure 70 Technology roadmap for lightning technology (S. K. Lee, Mogi, & Kim, 2009, p. 594)

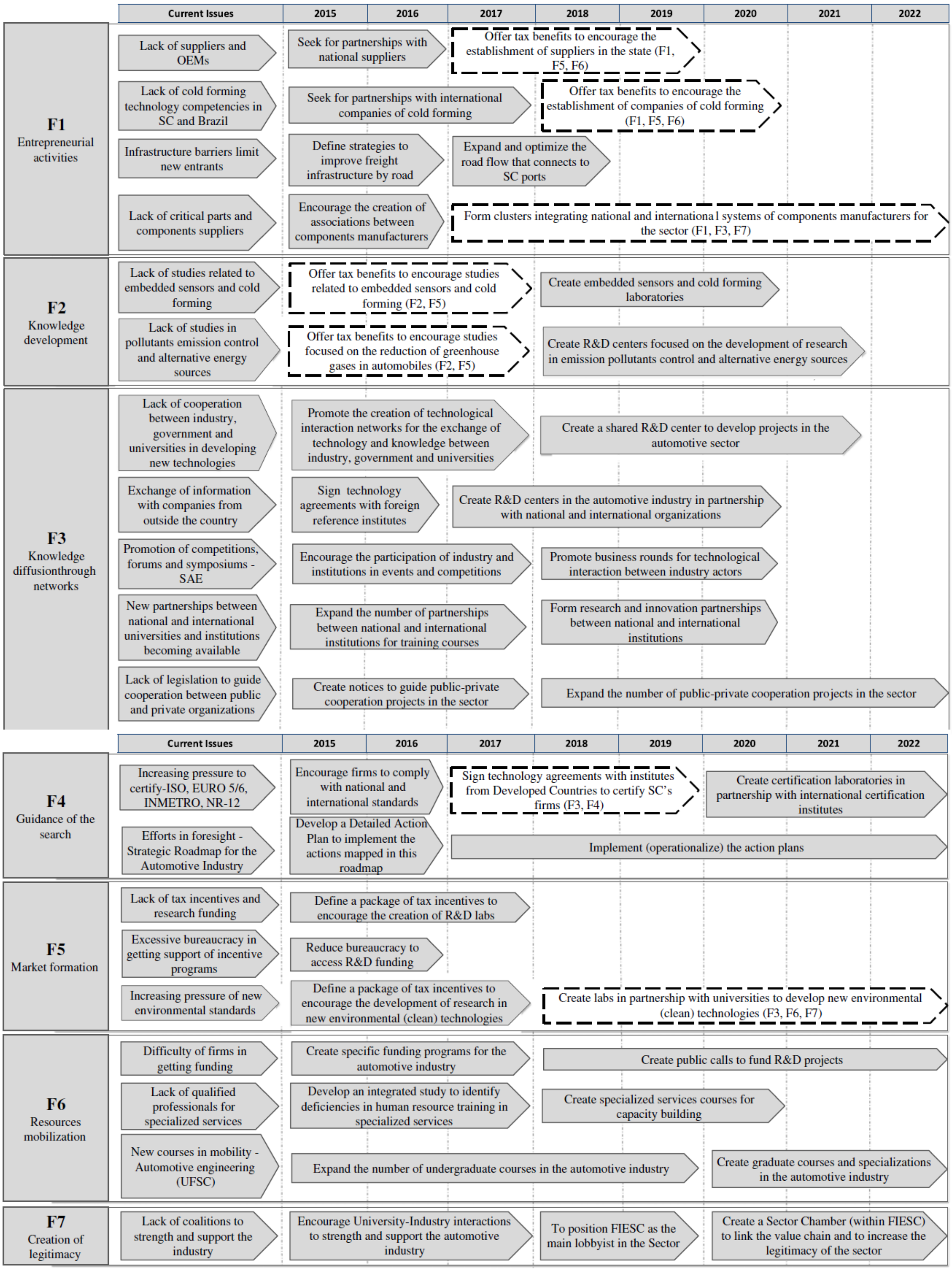


Figure 71 Technology roadmap for the automotive sector in Santa Catarina (Haddad & Uriona Maldonado, 2017, p. 258)

Appendix B - List of found Technology Roadmaps

ID	Title
IEEE1	The Energy and Variability Efficient Era (E.V.E.) is Ahead of Us (Deleonibus, 2016, p. 243)
IEEE2	Autonomous driving: a bird's eye view (Martínez-Díaz, Soriguera, & Pérez, 2019, p. 570)
SD1a	A regional technology roadmap to enable the adoption of CO2 heat pump water heater: A case from the Pacific Northwest, USA (Khanam & Daim, 2017, pp. 166–167)
SD1b	A regional technology roadmap to enable the adoption of CO2 heat pump water heater: A case from the Pacific Northwest, USA (Khanam & Daim, 2017, pp. 171–172)
SD2	Methodology for the of building process integration of Business Model Canvas and Technological Roadmap (Toro-Jarrín, Ponce-Jaramillo, & Güemes-Castorena, 2016, p. 222)
SD3a	Application of technology roadmaps to governmental innovation policy for promoting technology convergence (Yasunaga, Watanabe, & Korenaga, 2009, p. 65)
SD3b	Application of technology roadmaps to governmental innovation policy for promoting technology convergence (Yasunaga et al., 2009, p. 66)
SD4	An integrated service-device-technology roadmap for smart city development (J. H. Lee et al., 2013, pp. 300–301)
SD5	The future of rail automation: A scenario-based technology roadmap for the rail automation market (Hansen, Daim, Ernst, & Herstatt, 2016, p. 202)
SD6	A functions approach to improve sectoral technology roadmaps (Haddad & Uriona Maldonado, 2017, p. 258)
SD7	Development of the scenario-based technology roadmap considering layer heterogeneity: An approach using CIA and AHP (H. Lee & Geum, 2017, p. 22)
SD8	Smart manufacturing technology, market maturity analysis and technology roadmap in the computer and electronic product manufacturing industry (Lu & Weng, 2018, pp. 89–91)
SD9	Energy technology roadmap for the next 10 years: The case of Korea (S. K. Lee et al., 2009, pp. 594–595)
SD10	Technology roadmap study on carbon capture, utilization and storage in China (X. Zhang et al., 2013, p. 540)
SD11	Energy efficiency as a means to expand energy access: A Uganda roadmap (La Rue Can et al., 2018, p. 362)

ID	Title
SD12	Development of a technology roadmap for bioenergy exploitation including biofuels, waste-to-energy and power generation & CHP (Gonzalez-Salazar et al., 2016, pp. 344–345)
SD13	Analyses of CO2 mitigation roadmap in China's power industry: Using a Backcasting Model (Wen, Di, Yu, & Zhang, 2017, pp. 649–650)
SD14	Energy technology roadmap for ethylene industry in China (Chen, Yu, & Wei, 2018, p. 172)
SD15	Industrialization roadmap model for fermentative hydrogen production from biomass in Taiwan (Hsu et al., 2017, p. 27468)
SD16	Combining technology roadmap and system dynamics simulation to support scenario-planning: A case of car-sharing service (Geum et al., 2014, p. 44)
SD17	Conceptual framework to assess the impacts of changes on the status of a roadmap (Gerdsri et al., 2019, p. 29)
SD18	Developing a technology roadmap for construction R&D through interdisciplinary research efforts (Kim et al., 2009, pp. 335–336)
SD19	Development of a roadmap for advanced ceramics: 2010–2025 (Rödel et al., 2009, pp. 1553–1558)
SD20	Technology roadmap: Cattle farming sustainability in Germany (Gallegos Rivero & Daim, 2017, p. 4319)
SD21	A policy framework and industry roadmap model for sustainable oil palm biomass electricity generation in Malaysia (Umar, Urmee, & Jennings, 2018, p. 280)
SD22	Technology-driven roadmaps for identifying new product/market opportunities: Use of text mining and quality function deployment (Jin et al., 2015, pp. 134–136)
SD23	Low Carbon Technology Development Roadmap for China (Liu et al., 2011, p. 72)
SD24	A roadmap for carbon capture and storage in the UK (Gough, Mander, & Haszeldine, 2010, pp. 6–8)
SD25	ERRAC Roadmap WPO3: Urban, Suburban and Regional Rail and Urban Mobility (Hoogendoorn & Amsler, 2012, pp. 2290–2291)
SD26	Roadmap to a Sustainable Aviation Biofuel: A Brazilian Case Study (Cortez et al., 2016, pp. 345–348)
SL1	New Horizons for a Data-Driven Economy (Cavanillas et al., 2016, pp. 280–281)
SL2	Advances in Sustainable Manufacturing (Seliger et al., 2011, p. 205)
SL3	Technology roadmap for smart electric vehicle-to-grid (V2G) of residential chargers (Daim, Wang, Cowan, & Shott, 2016, p. 11)

Autor:innen

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Prof. Dr. Ralf Isenmann vertritt seit 2017 die Professur für BWL im Innovations- und Technologiemanagement am Fachbereich Wirtschaftsingenieurwesen und Technologiemanagement (WITM) an der WBH. Seine Schwerpunkte in Forschung und Lehre, Projekten und Publikationen liegen an den Schnittstellen zwischen Technologie- und Innovationsmanagement mit Schwerpunkten in Technologie-Roadmapping, Szenario-Analyse sowie Delphi-Methode einerseits und Nachhaltigkeitsmanagement mit Schwerpunkten in Sustainability Reporting, Industrial Ecology und Bildung für nachhaltige Entwicklung andererseits.

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