A ten-step framework for finding applications for a breakthrough technology

Partially applied to the case of quantum dots

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A TEN-STEP FRAMEWORK FOR FINDING APPLICATIONS FOR A BREAKTHROUGH TECHNOLOGY

PARTIALLY APPLIED TO THE CASE OF QUANTUM DOTS

By

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Preface

Thank you for reading this section. This document entails my second master thesis project, one of the final hurdles before completing my Double Degree in Chemical Engineering and Management of Technology at the TU Delft.

In this thesis I will show how one systematically finds possible future applications for a breakthrough technology. I partially apply this framework to the breakthrough technology of quantum dots (QDs).
QDs were the main topic in my first master thesis project during the fulfilment of the curriculum of Chemical Engineering. That I now, fifteen months later, not only have in-depth know-how about the technical side of a breakthrough technology (QDs), but also better understand the business and managerial perspectives of breakthrough technologies, makes me extremely proud.

The results that I managed to acquire would not have been possible without the help of Wijnand and especially Roland.
Wijnand, I want to thank you for the moments you were involved in this project. You have taught me to be critical at the results you gather and to sometimes take a few steps back before proceeding. It is safe to say that you surprised both Roland and me with your differing point of view. Next to this, you made me realise that it is not a bad thing to not understand everything and be proud of what you have accomplished so far (rather than predominantly looking at what it is you did not do).
Roland, what a journey this has been. It still buzzes me how alike we are and how enthusiastic you are, even after all those years at the TU Delft. You have been a great supervisor to me who always helped me when I needed it. I know I can be quite demanding and that I can be a pain in the ass from time to time. I really value the time you have taken for me, despite the fact that there are quite a few other students that you are currently supervising. You really listened to me, took the time to discuss topics, and treated me as *someone equal to you*. This is something that I have seldom come across during the six years I have spent at the TU Delft, and that many others can learn from. By doing this, you really motivated me to push even harder and it gave me the feeling I was *really contributing* to something. I want to thank you for everything you have done for me, and I wish you all the best in the years to come at the faculty of TPM.

After this master thesis project, I will leave the scientific world behind me (but perhaps only temporarily). I will take the summer break to explore what jobs are out there, learn the basics of Spanish, and most importantly *enjoy life!* When summer is coming to an end I will namely be travelling to Columbia, Costa Rica, and Mexico for three months. I am looking forward to all the lessons I will learn from this journey and enjoy some time off without any obligations. After that, I am very curious to see where my professional career will kick off…

If there is one lesson that I have learned during the current thesis project that I want to pass on to anyone reading this thesis, it would be the following: suffer the pain of discipline if you want to be successful.
During this project, as well as during my previous thesis, I have worked hard and in a very structured fashion from the beginning onwards. Because of this, I experienced barely any stress during the (final) stages of both projects. This is a lesson that has shaped me to a better version of myself and this is what I am most thankful for.

Jesse ‘t Hoen
Beverwijk, June 2023

Abstract

New Product Development (NPD) of applications incorporating breakthrough technologies can be beneficial for companies, but can also come with serious drawbacks. Therefore, the NPD process must be approached with great care. Rather than adopting the chaotic trajectory of the NPD process, where applications are introduced, withdrawn, and reintroduced naturally over time, business prosperity could be enhanced if companies can up-front formulate a set of possible future applications for a breakthrough technology. The most promising alternative can hereafter be chosen to be further developed in the NPD process, possibly reducing the chance of having to switch to the development of other applications (and thus circumventing the Collingridge dilemma). In this thesis, I start with defining the terms (breakthrough) technology and application. Then, I suggest a ten-step framework that is suited for formulating applications for a breakthrough technology, based on the comparison and symbiosis of five existent frameworks that are helpful in reaching the aforementioned goal. Factors that are of importance in that process are also investigated. None were discovered in scientific literature, but some suggestions are made based on the current work. The framework is applicable to breakthrough technologies of which it is non-obvious, and even unsure, what the technology can do, how it can be implemented into applications, and whom it might serve. Next to this, the breakthrough technology must still be in the innovation phase. The process itself must make use of qualitative and quantitative approaches in a balanced way, must continuously involve known sets of experts, must look into the future, and must formulate concrete applications for the emerging technology. The framework is then partially applied to the breakthrough technology of quantum dots (QDs). The technology profile and the application profile were gathered, first, based on scientific records. Then, the most frequently used keywords and the most increasingly used keywords were retrieved for both profiles. The most frequently used keywords showed that carbon dots are the most dominant area of research that is being conducted on QDs and that optics and imaging are the two major fields where QDs are being incorporated. The most increasingly used keywords confirmed the observation that QDs are in the adaptation phase, where QDs are still surrounded by substantial uncertainty. Finally, with the aid of text mining software of VantagePoint and programming software of R, two dendrograms were formed. The remaining steps of the framework were not carried out in the current thesis project. It was concluded that the ten-step framework is most likely better suited for breakthrough technologies that are more in their infancy than QDs (so, breakthrough technologies still in the innovation phase). The framework should, next to this notion of novelty, be applicable to any breakthrough technology, regardless of the field that the breakthrough technology is situated in. As long as it is non-obvious, and even unsure, what the breakthrough technology can do, how it can be incorporated into applications, and whom it might be useful for.

Keywords: breakthrough technology, finding applications, framework, quantum dots

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1. Introduction

In this introductory chapter the main concepts of this proposal are presented. In addition, the gap in scientific literature that forms the research problem is formulated. The research objective of this thesis and the associated research questions that need to be answered are also stated and discussed. Finally, the scientific relevance and managerial relevance of this project are specified.

1.1 Research background

Technologies can be subdivided into two classes: products and processes (Tushman & Anderson, 1986). They are the knowledge, devices, and tools that foster new products or services and bridge between inputs and outputs, respectively.
Technologies are not constant. Technological change is a complex phenomenon. The transformation of a technology is usually step-by-step and incremental after a dominant design, the product form or process that has won the standardisation battle and ends the 'era of ferment' (Anderson & Tushman, 1990), has been established. However, sometimes a more radical technological change presents itself. This discontinuity can lead to a major enhancement in the price-performance ratio or can result in new product classes. Such a breakthrough ushers in a new era of ferment until a dominant design emerges once again. The resultant technology of the latter type of technological change can be what is defined as a *breakthrough technology* (Ortt, Langley, & Pals, 2007). An example of a breakthrough technology that improved the price-performance ratio is Kevlar in the fibre industry, and an example of a breakthrough technology that led to the rise of a new product class is the television in the field of communication.

Once a breakthrough technology reveals itself, companies can develop products, processes, or services out of it. These innovations can thereafter be brought to market. The gradual adoption in a market sector, or even a society, of such an innovation is what is commonly designated as *diffusion* (Ortt & Schoormans, 2004). Diffusion curves that map the percentage of adoption as a function of time are frequently S-shaped (Rogers, 1962). They reflect an initial stage of slow adoption, followed by an accelerated period of large-scale adoption, and reach an asymptotic value that displays the maximum of an innovation's total market potential.

Breakthrough technologies can be beneficial for companies (Ortt et al., 2007). Bringing them to market can namely contribute towards a company's (sustained) competitive advantage, as they can surface new product classes and sometimes even lead to the rise of new markets or even industries (Olleros, 1986). Examples that can be thought of are the rise of low-cost nonmedical fentanyl and cannabis due to a breakthrough in their production process (Caulkins, 2021), the appearance of electronic watches opposed to mechanical watches within the watch industry (Olleros, 1986), and the emergence of the solid-state lighting industry through the invention of light-emitting diodes (Sanderson & Simons, 2014).

However, breakthrough technologies can also come with drawbacks. Developing them and bringing them to market can be a huge risk for companies. Olleros (1986) states that only few companies do not fail miserably when bringing breakthrough technologies to the market. The scientist attributes this failure to multiple factors, e.g., high market uncertainty and high technological uncertainty. The numbers are confirming this discouraging narrative. Many market pioneers (47%) vanish into thin air and only a minor percentage (11%) of this group can establish a market leader position (Tellis & Golder, 2006). Pioneers are often overtaken by early leaders, who on average follow the footsteps of pioneers thirteen years later, nevertheless being more successful. Examples of companies that were first to market but failed to survive are MITS (personal computer industry) and The Stanley Brothers (automobile industry) (Olleros, 1986).

Looking at the dichotomy sketched above, it can be concluded that developing breakthrough technologies, and bringing them to market, must be handled with great care. On the one hand there is the potential of profitability and growth, but on the other hand there is the risk of failing miserably.

In the early development stages of the commercialisation of a breakthrough technology, there are often multiple, competing technologies in circulation. Each of these technologies, in turn, has various, competing applications that are being developed. During these uncertain times, termed the 'adaptation phase' by Ortt and co-workers (Ortt et al., 2007), products, processes, and services incorporating a new breakthrough technology are introduced and withdrawn from the market frequently, until a dominant design emerges. Having to withdraw an innovation from the market can be accompanied by great costs and can consume significant time and resources, threatening innovative firms.
It would therefore be of use if companies can abandon this chaotic trajectory of moving from one application to the other. Instead, it would be advantageous if firms can systematically generate a set of possible applications for a breakthrough technology at the start of the innovation process. The most promising alternative can then be developed, possibly reducing the chance of having to withdraw a product, service, or process from the market. As of now, only limited research has been carried out to better structure the innovation process as discussed.

In this report, a framework will be designed that allows for the systematic formulation of a set of possible future applications for a breakthrough technology. Part of this framework will be effectuated on the breakthrough technology of quantum dots (QDs). QDs are nanocrystals of semiconductor materials (Guyot-Sionnest, 2008). They exhibit some interesting properties, e.g., the emission of single-wavelength photons upon excitation, depending on the size of the crystals. Multiple applications that implement this invention are being developed as we speak, think of innovations in the healthcare sector (Jamieson et al., 2007; Medintz, Mattoussi, & Clapp, 2008) and applications in optoelectronics (Song et al., 2022; Terada, Ueda, Ono, & Saitow, 2022). However, as far as I know, no systematic analysis has been carried out that examines which possible applications for QDs can be thought of. A business-centred approach will be adopted. In other words, the view of companies will be central, opposed to e.g., a governmental perspective.

1.2 Research problem

Although not crucial for company survival in the long run per se, as claimed by Coyne (1986), (sustained) competitive advantage can increase firms' ability to endure. This sustained competitive advantage and thus the ability of firms to survive is influenced by many factors. Next to age of the firm (Cefis & Marsili, 2005; Sutton, 1997), its financial and profitability constraints (Bellone, Musso, Nesta, & Quéré, 2008), and the characteristics of the market (Agarwal & Gort, 2002; Mata, Portugal, & Guimarães, 1995), to name a few, innovative activity is a prominent factor (Ortiz-Villajos & Sotoca, 2018). In line with the narrative set forth in section **1.1 Research background**, conflicting findings on the relationship between innovative activity and company success have been found. While some scientists indicate that there is a positive influence of innovative activity on business prosperity (Børing, 2015; Buddelmeyer, Jensen, & Webster, 2009), others hint towards the lack of such a correlation (Jensen, Webster, & Buddelmeyer, 2008). This contrast reinforces the earlier statement that innovative activity, spanning from the creation of new ideas to the implementation of those ideas into products, services, or processes in a company, should be handled with great care.
This entire process is often referred to as New Product Development (NPD) (Ernst, 2002). To approach NPD with great caution, the process should be initiated with a sound starting point. Most commonly, however, this solid foundation is lacking, making the course of the NPD process chaotic. Often, an application of a breakthrough technology is being developed, and as obstacles surrounding this application are encountered as time goes by, this particular

application is being withdrawn from and reintroduced to the market (in a different form). Rather than pursuing this chaotic trajectory, which can consume significant amounts of a business' scarce time and resources due to the multiple cycles of introduction, withdrawal, and reintroduction, it would be better if companies know up-front of the NPD process which possible applications can be thought of for a breakthrough technology. Then, when all alternative applications are known, the development of the most promising application can be pursued. Although this application could still be surrounded by an evolutionary trajectory of introduction, withdrawal, and reintroduction, the chances of this happening could be reduced. The 'right' application is namely developed from the start. In the chaotic NPD process, the application that is being developed might not be the most suited one and this is only discovered as the process proceeds (and significant investments have thus already been made).

The more structured vision of the NPD process is illustrated in **Figure 1.2.1** below. The beginning of this process, which I term the pre-Fuzzy-Front-End phase, is the topic central to this thesis. The NPD process from the selection of the most promising application onwards falls out of the scope of the current project.

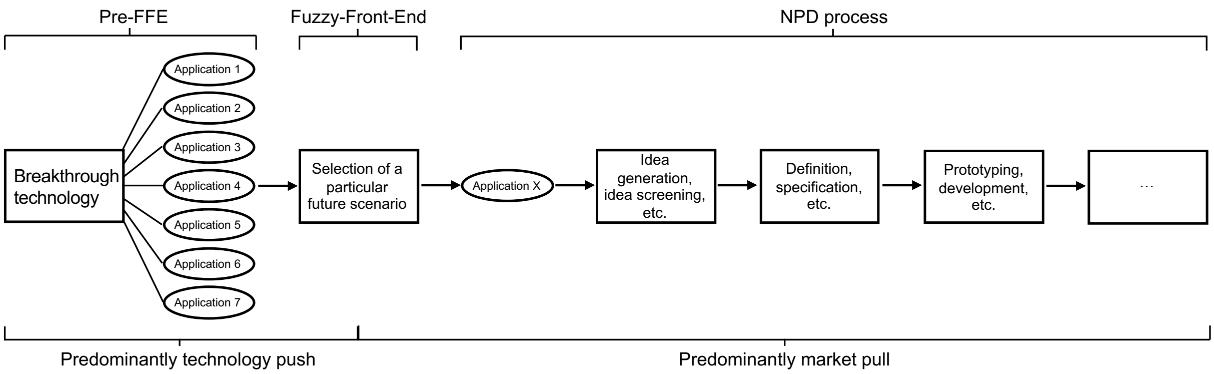

Figure 1.2.1. The total NPD process as I envision it. The problem addressed in this thesis is located in the pre-FFE phase, being the very start of the NPD process when the breakthrough technology has just surfaced.

As time passes by (from left to right) in the (above) NPD process, increasingly more information surrounding the application for the breakthrough technology becomes available. However, the ability to steer the NPD process to different directions based on the improved information basis becomes increasingly more difficult. This phenomenon is commonly known as the Collingridge dilemma (Worthington, 1982). The Collingridge dilemma suggests that in the early stages of technology development, when there is limited information and control, it is difficult to regulate the technology effectively. However, once the technology is well-established and its impacts are more apparent, it may be too late or too challenging to implement significant control measures.

Having a list of possible future applications for a breakthrough technology, and thus being better able to evaluate which path to pursue, could reduce the chance of having to steer the NPD process to different directions later on in the process.

Therefore, to aid mitigating the Collingridge dilemma, it would be of use if companies can systematically find possible future applications for a breakthrough technology. On top of this, it would be beneficial if enterprises can understand which factors play a determining role in this process. To the best of my knowledge, a framework describing these two phenomena does not exist, yet.

1.3 Research objective and research questions

The main objective of this research project will be setting up a framework that allows for finding applications for a breakthrough technology. The factors that are of importance in this process will also be investigated. Once the framework is formulated, and the success factors are found, it will partially be used to forecast which applications one can formulate for the breakthrough technology of quantum dots.

To reach the objective, the following research (sub)questions are formulated:

- **(1)** How can one systematically find applications for breakthrough technologies?
  - **(1.1)** How can a (breakthrough) technology be defined?
  - **(1.2)** How can an application be defined?
  - **(1.3)** What methodologies for creating a list of applications for a breakthrough technology are existent?
  - **(1.4)** What are factors influencing the process of formulating applications for an emerging technology?
  - **(1.5)** How can a set of possible future applications for a breakthrough technology be formulated by taking the discovered methodologies and factors into account?
- **(2)** Which possible future applications can be found for quantum dots?

1.4 Scientific and managerial relevance

As stated earlier, the NPD process is accompanied by a high failure rate. If, before developing one particular application, one can assess an extensive set of possible applications, this failure rate might decrease. If it is known which alternative applications exist, a more thought-out decision can be made on which application to devote a business's scarce time and resources towards. Until present, only limited records have been published that describe how a set of possible future applications for a breakthrough technology can be formulated. Within this report, I first give more clarity regarding the multifaceted terms (breakthrough) technology and application. The terms are namely used in a variety of manners and in a variety of dimensions in scientific literature. Then, I discuss those frameworks that are useable for reaching the just mentioned goal and compare them to each other, which is something that has not been done before. The factors that are of importance in this process are not documented in literature, and these factors are investigated and presented in the current work. A framework that shows how one finds applications for a breakthrough technology, with the definitions as provided in the current work, is non-existent in the scientific world. Based on the comparison of the relevant frameworks, a framework is composed that can be used for this purpose. Put differently, the current work tries to give structure to a process that is exceptionally uncertain in nature by providing tangible handles to manage it.
The aforementioned points make the current research managerially relevant since it allows managers to better approach the extraordinarily uncertain NPD process and possibly reduce the failure rate of their NPD projects. Frameworks for reaching this purpose are currently absent, and therefore it is also scientifically relevant to design a framework for finding applications for a breakthrough technology.

The scientific interest as well as the managerial interest into quantum dots, the breakthrough technology where the constructed framework will be partially applied to, has increased significantly over the past two decades, as is obvious from **Figure 1.4.1** on the next page.

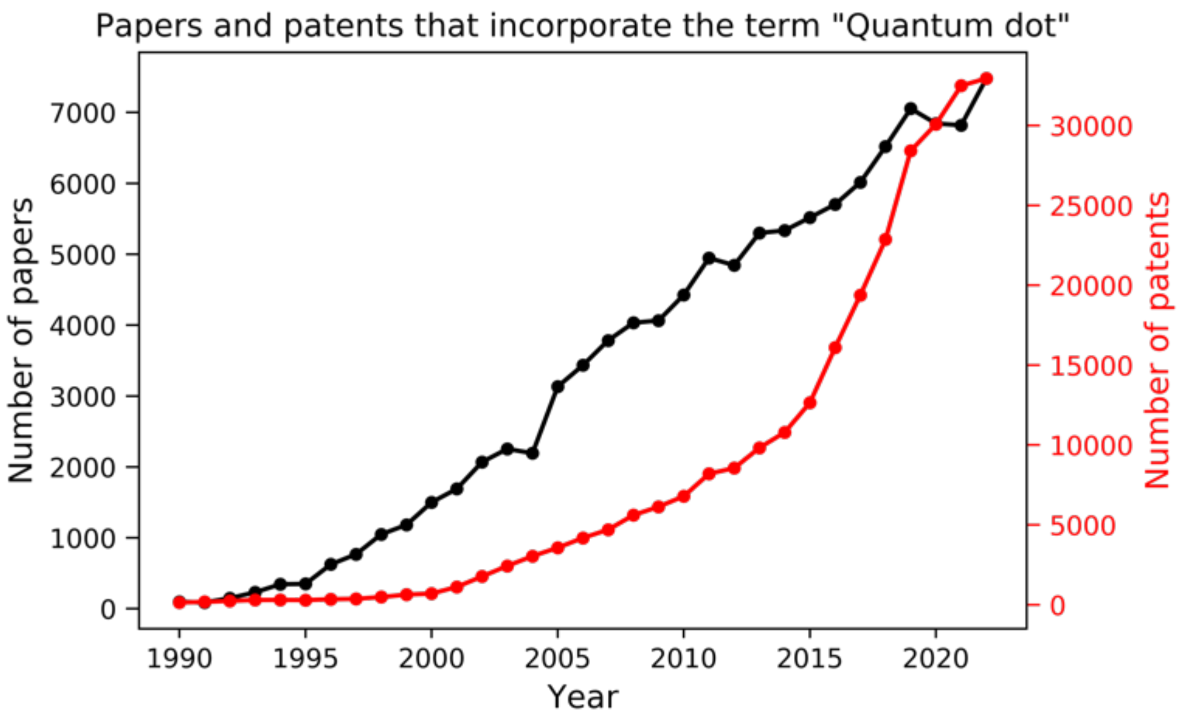

Figure 1.4.1. The number of papers (black, source: Scopus) that use the term 'Quantum dot' in their abstract and the number of patents (red, source: European Patent Office (EPO)) that have the term 'Quantum dot' in their abstract or applicant name during the last 32 years.

The figure shows that the number of published papers that use the term 'Quantum dot' in their abstract has increased from almost zero in 1990 to over 7,000 in 2022. This visualises that the scientific world is increasingly interested in, and conducting research on, QDs. This observation shows that it is scientifically relevant to use QDs as an example to illustrate which applications for a breakthrough technology can be found.
The figure also shows that the number of filed patents that use the term 'Quantum dot' in their abstract or applicant name increased from almost zero in 1990 to over 30,000 in 2022. This envisages that the translation from basic research into applied research is increasingly being made and that businesses also show increasing interest in QDs. The graph shows that it is thus also managerially relevant to use QDs as an example to demonstrate which applications for a breakthrough technology can be found.

The current thesis is structured as follows. Section **2. Defining and/or explaining relevant concepts** covers an in-depth definition and/or explanation of the core constructs that are needed to comprehend this proposal. Section **3. Research methodology** elaborates on the research methodologies that will be implemented to reach the research objective and answer the accompanied research questions. Section **4. Frameworks and factors** covers the frameworks and factors that were found. In section **5. A ten-step framework for finding applications for a breakthrough technology, partially applied to quantum dots** I propose a ten-step framework for finding applications for a breakthrough technology and partially apply this framework to the breakthrough technology of QDs. Penultimate section **6. Discussion and future research** discusses the results of this thesis. This section also hints towards possible directions for future research. Finally, in section **7. Conclusion**, the current project is concluded.
The build-up of this report is summarised in **Figure 1.4.2** on the next page.

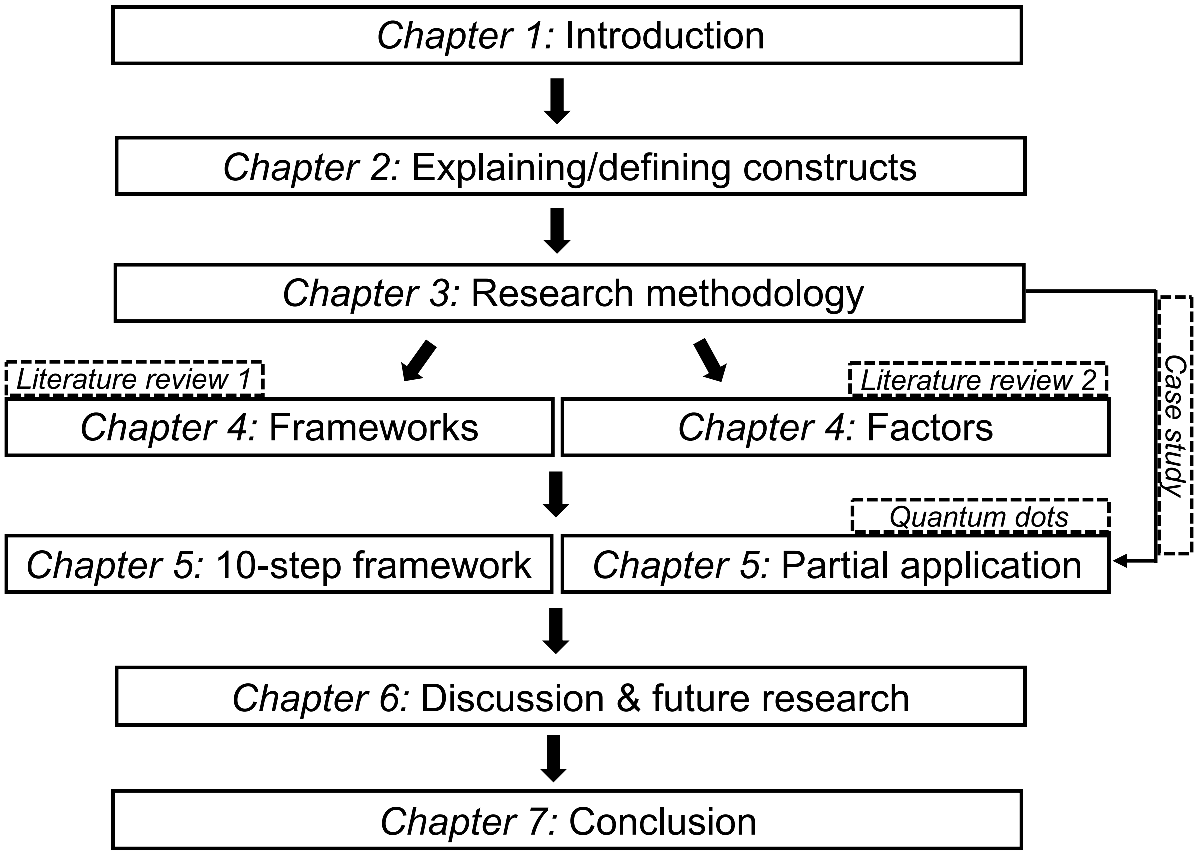

Figure 1.4.2. Build-up of the current thesis report.

2. Defining and/or explaining relevant concepts

This chapter defines and/or gives more in-depth insights into the main concepts of this research project. It starts with discussing (breakthrough) technologies and the constructs of innovation and application. Building forth on these constructs, the concept of uncertainty is reviewed. Finally, development and diffusion and the exemplary breakthrough technology of this thesis, quantum dots, are elaborated upon.

2.1 Technology

The term 'technology' has been observed and defined from different points of view over the years (Wahab, Rose, & Osman, 2012). Therefore, many divergent definitions of the construct are in circulation. This showcases the abstractness of the concept. It is thus first needed to understand how technology is defined and consequently how technologies can change over time.

2.1.1 Defining technology

In their literature review, Wahab et al. (2012) list nineteen findings of different definitions of the term 'technology' in chronological order. They conclude that, on an all-encompassing level, technologies showcase two main components. Firstly, technology entails a technique or knowledge and, secondly, technology comprises "doing things".
The existent literature that goes about technology is inconsistent regarding the dimensions on which technology is examined. As means of illustration, some authors mention nanotechnology as being a technology (Malanowski & Zweck, 2007; Sastry, Rashmi, Rao, & Ilyas, 2010; Wiek, Gasser, & Siegrist, 2009), whereas other authors claim Solid Lipid Nanoparticles (SLNs) to be a technology (Zhou, Huang, Porter, & Vicente-Gomila, 2019). The former is, in my opinion, more a domain or a field than a technology. Then, within the field of nanotechnology, there are multiple technologies present, such as SLNs or QDs.
Extending on this, I define technology as the tools or knowledge that can be used to create and produce goods and services, solve problems, and facilitate (new) products. This definition coheres to a great extent with the definition of e.g., Tushman and Anderson (1986). Dimension-wise, a technology is the smallest unit of analysis within a domain or field. A technology thus is the basis of what can be done in principle on top of what is done in actuality within a certain field (Clarke, Weyant, & Edmonds, 2008). Examples of technologies are light-sensitive cells, solid lipid nanoparticles, and just-in-time (JIT) manufacturing.

2.1.2 Technological change

Technologies are not constant. Alterations in technologies can for instance lead to renewal of a production process, resulting in cheaper products. This phenomenon modifies the shape of the production function and is commonly referred to as technical change (Acemoglu, 2002). However, a more all-encompassing term that incorporates technical change as well as the development of *new* products and services, is technological change (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007). The two terms are often used interchangeably in management of technology literature, although there is a fundamental difference in their meaning. Technological change is complex and generally known to be the driving factor for economic growth (Schmookler, 1965). This is recently confirmed by Sredojević, Cvetanović, and Bošković (2016), who showed that three major growth theories (evolutionary, new or endogenous, and classical) all support this statement. However, the mechanism that causes economic growth has long remained absent. It was merely assumed that technological change leads to economic growth. Only recently Shiozawa (2020) revealed that technological change leads to improved income per capita and real wage rates, and that these two resultants influence economic growth.

Drivers for technological change are numerous. A common dichotomy in the source of technological change is the distinction between technology push and market pull (Boehme, 1986; Brockhoff, 1969; Bullinger, 2013; Schön, 1967).
Technology push refers to the development of new technologies driven by advancements in science and engineering. In this approach, technological innovations are created because of research and development efforts, often driven by companies (either internal or external), universities, and other organisations that are focused on discovering new and improved technologies. The goal of technology push is to create new technologies that can be commercialised and applied in a variety of industries and applications. The demand side of the market is unknown in most cases of technology push projects (Henkel & Jung, 2009). Technology push is therefore sporadically used (Kostoff & Schaller, 2001), compared to market pull, since it is seen as time-consuming and more difficult (Herstatt & Lettl, 2004).
Market pull, on the other hand, refers to the development of new technologies driven by consumer demand and market forces. In this approach, innovation is driven by the need to meet the demands and needs of customers and the market. Companies and organisations focus on understanding customer needs and creating products and services that meet those needs. The goal of market pull is to create new technologies that are relevant, useful, and desired by consumers. Here, there is an (unsatisfied) demand from the market that is central to the technological change.
More recent literature states that all possible sources of technological change are hardly ever included in models (Clarke et al., 2008). This research and that of Clarke, Weyant, and Birky (2006) identifies that learning-by-doing and R&D practices within and industry, as well as knowledge spillovers from differing industries, are driving factors for technological change. These views are in line with the technology push approach. Coccia (2017) mentions that technological change is problem-driven, meaning that companies mainly endeavour in technological change because they want to come up with solutions to existing problems. This view is more in line with the market pull approach.
On top of this, Bruun and Hukkinen (2003) state that technological change can be explained by three alternative ways of thinking, evolutionary economics (EE), social construction of technology (SCOT), and actor-network theory (ANT), and that there are connections between these views rather than them being unrelated and opposing views.
Based on the above, it seems that the origin of technological change is multifaceted and most likely not fully understood by the scientific world.

The process of how technological change takes place can either be linear and step-by-step or discontinuous and drastic. The first process is commonly referred to as incremental technological change, whilst the latter is often termed radical technological change (Norman & Verganti, 2014). Whereas incremental technological change is proverbially concerned with climbing the hill of a mountain towards its top, radical technological change deals with finding the mountain with the highest top.
Incremental technological change comprises minor changes in an existing technology to improve the desirability, lower the associated costs, or improve the performance of products and processes that incorporate the technology. This makes incremental technological change an important way of innovating. This is the dominant means of innovating, and an example of incremental technological change is the improvement of a software algorithm that is used in a certain product.
A more sensational, less common way of innovating comes in the form of radical technological change. Instead of being a continuous alteration of an existing technology, here the technological change is unique, new, and discontinuous. Radical technological change can offer enterprises the ability to differentiate but it is also accompanied with a high failure rate. Dahlin and Behrens (2005) suggest three criteria that technological change needs to adhere to for it to be classified as radical: (1) it must be novel, (2) it needs to be unique, and (3) it needs to be adopted. The third criterion makes that innovations that are not adopted are not seen as radical. I think this is problematic, because that are certainly some innovations that

can be seen as radical, despite them not being adopted. One such example is the Segway Personal Transporter.

2.2 Breakthrough technology

Radical technological change is often associated with *breakthrough* technologies. This is the type of technology that is central to this proposal and is therefore further elaborated on. Here, the discontinuity of the radical technological change is so profound that it can potentially lead to a major enhancement in the price-performance ratio of existing products, processes, or services, or even result in new product classes (Ortt et al., 2007).
The emergent stage of breakthrough technologies is accompanied by unique circumstances. Whereas the classical view in literature states that either the technological dimension (TD) or the usage dimension (UD) is evidently known during the emergence of a technology, both dimensions are unstable during the emergence of breakthrough technologies (Gillier & Piat, 2011). In the beginning, it remains unclear what can be done with a breakthrough technology and who the technology can serve. This separates the emergence of a *breakthrough* technology from that of a regular technology. For regular technologies, it is often clear what the technology can do and/or by whom the technology can be utilised.
Breakthrough technologies can lead to *creative destruction*, as termed by Schumpeter (Schumpeter, 1942). Creative destruction describes the process by which new innovations and technologies lead to the decline and eventual replacement of established industries and businesses. The basic idea behind creative destruction is that the introduction of new and better technologies and business models disrupts and displaces existing industries and firms. This process can be painful for those who are affected, as jobs and entire industries may be lost, but it also creates new opportunities and growth. As old industries and firms decline, new industries and firms emerge to take their place, often with more efficient and innovative approaches.
Breakthrough technologies can potentially also be *disruptive*. The construct was first coined by Christensen in his 1997 book titled 'The Innovator's Dilemma' (Christensen, 2013). The theory states that incumbent firms are sustaining innovation by regularly improving their current products, processes, and services. At some point, the pace of these sustaining innovations exceeds the existing customer demands. In other words, innovations become too competent. They have many features that are not used by customers. This mismatch gives room for simpler, often cheaper products, processes, or services. These innovations typically start out serving niche markets or low-end customers, and gradually improve in performance and functionality over time until they become good enough to challenge established players and the existing business models that may overlook or dismiss the potential of disruptive technologies.

The two characteristics narrated above show that applications that are based on breakthrough technologies have benefits as well as drawbacks. On the one hand they can lead to new, more efficient, and more innovative industries and firms. On the other hand, they can literally destroy incumbent ones. Examples of such applications that showcase this are the rise of Netflix (and the downfall of Blockbuster) and the replacement of horse-drawn carriages by automobiles.

2.3 The trio of breakthrough technology, innovation, and application

Once a breakthrough technology reveals itself, companies can formulate products, services, and processes that incorporate this technological principle. By doing this, the breakthrough technology moves towards an *innovation*. Consequently, innovations can be turned into *applications.* There is a subtle difference in the interpretation of the two last mentioned concepts, which is elaborated upon below. Especially the construct of an application is defined carefully and precisely, as it is one of the core constructs to this proposal.

Breakthrough technologies are discussed in the preceding section. When a breakthrough technology reveals itself, it is often not immediately obvious in what product, service, or process the technology can be incorporated. Let us consider the example of a light-sensitive cell. This breakthrough technology can be implemented in several products, think of e.g., solar cells, sensors, and cameras.

Innovation is defined in a plethora of ways (Kogabayev & Maziliauskas, 2017). Verbalising a wide-ranging definition is not an inornate task, but one definition could be: “the creative process whereby new or improved ideas are successfully developed and applied to produce outcomes that are practical and of value” (Taylor, 2017, p. 131).
As early as 1934, Schumpeter formulated five types of innovation (Schumpeter, 1934):

1. New product or service innovation: this involves the introduction of a new product or service that is not currently available in the market, or an improvement of an existing product or service.
2. Process innovation: this involves the development of new methods or techniques for producing goods and services or improving the efficiency and effectiveness of existing production methods.
3. Market innovation: this involves finding new markets for existing products or services, or creating entirely new markets through novel distribution channels, pricing strategies, or other means.
4. Organisational innovation: this involves changing the organisational structure, management practices, or culture of a company to improve its performance, increase efficiency, or better meet the needs of its customers.
5. Technological innovation: this involves the development of new technologies, or the improvement of existing ones, that can lead to new products, processes, or services.

Expanding their view even further, Keeley, Walters, Pikkel, and Quinn (2013) even recognised ten types of innovation. Since there are many definitions and types of innovation, I choose to demarcate the definition of an innovation that is being used in this proposal. I define an innovation as the incorporation of a technological principle that is introduced to the market, has a particular functionality, and is made up out of several subsystems. An innovation can be a product, service, or production technology that is new or significantly improved from previous versions. An innovation must thus meet the following requirements:

- Technological principle: an innovation must be centred around a fundamental scientific or engineering concept or theory.
- Functionality: an innovation must be able to carry out its intended use or function effectively.
- Subsystems: an innovation must be composed of a set of components.

This definition of an innovation focuses more on new product innovation than on the other categories as specified by Schumpeter (1934). Additionally, this definition emphasises the supply side of the market (technology push).
Returning to the technological principle of a light-sensitive cell, an example of an innovation could be a camera. A camera is based on the technological principle of a light-sensitive cell, as mentioned above, has the functionality of capturing a scene, and is made up out of several subsystems (think of the lens, the shutter, the light-sensitive cell, and the flash, among others).

Following the definition of Hornby (2010, p. 61), an application is “the practical use of something, especially a theory, discovery, etc.”. An application is thus a specific use case or implementation of an innovation. In other words, an innovation can be thought of as a general product, process, or service, while an application is a specific instance or use of that innovation. An innovation can be recognised as an application when it is implemented or utilised in a specific context or setting, and when it provides a tangible benefit or advantage over existing approaches or technologies. An application is essentially an illustration of the innovation being used in practice to address a particular problem or need. An application contains the requirements of an innovation and must, on top of this, meet the undermentioned requirements:

- Customer group: an application must serve a certain social unit.
- Preference: an application must, by means of its functionality, fulfil an explicit set of preferences of the customer group.
- Usage context: an application must aid the customer group in a particular setting.

This definition of an application lays more emphasis on the demand side of the market (market pull).
Let us reconsider the camera. The camera is defined as an innovation but lacks the crucial requirements of an application. The device itself namely has no specified customer group, does not serve a set of preferences, and is not used in a particular context. The camera will only be classified as an application when, by means of example, it is introduced to adults that want to capture moments while being on holiday. Now the innovation has a customer group, adults, supports certain preferences, capturing moments, and does so in a specific context, being on holiday. These requirements can be specified further. For instance, one could say that the group of adults must be between 30 and 40 years of age and have multiple children, wants to capture moments in at least 4K HD, and goes on holiday to Italy. However, such narrowing of the scope is part of the analysis of an application rather than of its definition. If the requirements change to, e.g., adolescents that want to livestream while playing videogames, the resultant application will be a completely different one. Whereas the adults require no internet connection because they will mostly review the photographs and videos in hindsight, the adolescents need the camera to be able to upload whilst recording. In addition to this, battery life is way more important for the adolescents than for the adults. Also, the adults need the camera to be portable, whereas the adolescents would not mind if the camera was stationary. This example showcases how different applications of the same innovation come about and that this differentiation finds its origin in the demand side of the market (market pull).

2.4 Uncertainty

The development of innovations and applications that incorporate breakthrough technologies is surrounded by substantial levels of uncertainty. Uncertainty is described as the incomplete presence of knowledge about the likelihoods of the future state of events (*cf.* Knight, 1921). It is a situation in which the possible outcomes cannot be known, and probabilities cannot be estimated. Uncertainty should thus not be confused with risk, which is a situation where the possible outcomes can be well-known, and their probabilities can be predicted.
The construct of uncertainty has been dealt with by many studies but the concept is often treated inconsistently (Sniazhko, 2019). A clear distinction between the diverse dimensions of uncertainty is habitually lacking. Sniazhko (2019) distinguishes thirteen types of uncertainty that influence corporate decision-making and groups them into three categories: environmental, firm, and industry. Focusing more on the interrelation between uncertainty and innovation, Jalonen (2012) formulates eight categories of uncertainty in innovation processes. The latter collection of uncertainties and how they are manifested in innovation practices is summarised in **Table 2.4.1** on the next page. Uncertainty is one of the key factors underlying the failure of companies that develop innovations and applications incorporating breakthrough technologies (Olleros, 1986). Therefore, it is beneficial to understand what types of uncertainty are present in the innovation process and how these uncertainties are manifested.

Table 2.4.1. Eight types of uncertainty and how they are manifested in innovation practises. Adapted from Jalonen (2012).

Uncertainty factor	Manifestation of uncertainty
Technological uncertainty	– Due to the novelty of technology its details are unknown – Uncertainty regarding knowledge required to use new technology
Market uncertainty	– Unclear customer needs – Lack of knowledge about the behaviour of competitors – Difficulties in predicting the price development of raw materials and competing products and services
Regulatory/institutional uncertainty	– Ambiguous regulatory and institutional environment
Social/political uncertainty	– Diversity of interests among stakeholders of innovation processes – Power struggle
Acceptance/legitimacy uncertainty	– Necessary skills and knowledge contradict existing skills and knowledge possessed by perceived users of innovation – Innovation threatens individual's basic values and/or organization's norms
Managerial uncertainty	– Fear of failure – Lack of requisite tools to manage risk inherent in innovation process
Timing uncertainty	– Lack of information in the early phases of innovation – Ambiguity of information in the late phases of innovation – Temporal complexity
Consequence uncertainty	– Indirect consequences – Undesirable consequences – Unintended consequences

Perhaps counterintuitively, uncertainty can have positive effects on the innovation process (O'Mahony, 2023). Uncertainty can spur innovation practices. If companies embrace it, they might be able to find new products, services, and technologies that would not have emerged if contexts were certain. Christensen (2013) reinforces this statement by narrating that uncertainty is inherent to and one of the drivers of innovation. Firms that are successful in finding new customer needs, rather than exploiting current customer preferences, are more likely to succeed in developing disruptive innovations. Vo and Le (2017) state that firms that face high levels of uncertainty tend to spend more on R&D investment, which can be a pivotal parameter in the innovation process.

However, uncertainty and innovation practices are often negatively correlated (Bolli, Seliger, & Woerter, 2020; Bonciani & Oh, 2022; Yu, Xiao, & Li, 2021). Zhang (2015) declares that firms that operate in target markets with future uncertainty tend to abandon or postpone innovation projects due to the high adjustment cost and inflexibility of R&D investment (*cf.* the Collingridge dilemma). Another example surfaces in the form of political uncertainty. During national election periods innovation activity namely tends to plummet significantly (Bhattacharya, Hsu, Tian, & Xu, 2017).

Since uncertainty shows to be detrimental as well as lucrative to innovative activity, there is widespread literature available on how companies manage uncertainty in the innovation process. Many scholars focus on managing the initial stage of the innovation process, often referred to as 'the fuzzy front-end (FFE) of innovation' (van Aken & Nagel, 2004). This stage is called fuzzy because it represents a time of ambiguity, uncertainty, and exploration, where the exact scope and definition of the project are not clear, yet. Numerous best practices to manage the FFE of innovation are in circulation. For instance, Kakar and Carver (2012)

describe ten best practices to manage the FFE of innovation. These strategies include formalising the innovation process, developing a shared mission amongst team members, and making sure that managers are aware of decision biases, among others.
A way to deal with uncertainty that has generated increased scientific interest over the past decades is that of (organisational) ambidexterity (Ragazou, Passas, Garefalakis, & Dimou, 2022). Ambidexterity aims to explore new knowledge, markets, and technologies, while also exploiting the ones that are currently being used, simultaneously. In this way, the uncertainty that is mostly present in the exploration part is balanced by the more certain environment of the exploitation activities. Ambidexterity can be accomplished by a plethora of strategies. For example by using the agile project management methodology of scrum (Sailer, 2019), which incorporates sequential exploration and exploitation activities, or by setting up separate business units that specifically focus on either exploration or exploitation actions (Foss, Lyngsie, & Zahra, 2015).

2.5 Development and diffusion

This paragraph describes the process of how applications that incorporate breakthrough technologies come about and consequently how they can be introduced to the market. The first phenomenon is referred to as development, the latter one is known as diffusion.

2.5.1 Three phases in the development and diffusion of applications

Almost twenty years ago, Ortt and Schoormans (2004) published a paper entitled: “The pattern of development and diffusion of breakthrough communication technologies”. Here, five breakthrough communication technologies are analysed with respect to their development and diffusion. The authors discovered that the traditional S-shaped curve that is often used to describe diffusion phenomena, is incomplete. The curve should not be used for technologies but rather for product forms. They conclude that for breakthrough communication technologies, the S-shaped curve is only applicable to the last phase of its development and diffusion pattern. This so-called ‘market stabilisation phase’ is preceded by an ‘adaptation phase’, which is in turn preceded by an ‘innovation phase’. All phases last, on average, approximately a decade.

The innovation phase starts at the invention of a technology and runs until the first market introduction of a product or service that implements this technology. A rudimentary form of a technology is present right after its invention, and within the innovation phase this fundamental technology is implemented in a marketable service or product. This period is of uttermost importance for the current thesis project. In the beginning of this phase the breakthrough technology has just surfaced, and it is still completely uncertain where the technology can be used and whom applications that incorporate the technology can serve. It is the beginning of this period that is very suited for the formulation of a set of possible future applications for a breakthrough technology, so that the consecutive phase can be more streamlined.
The phase that follows, being the adaptation phase, runs from the first market introduction of a service or product that uses the breakthrough technology until the large-scale diffusion of this product or service kicks off. Once the product or service has been introduced to the market, an erratic process of diffusion may appear rather than the formation of one smooth S-shaped curve that resembles the diffusion process. Since the market is unstable at this time and technological uncertainty is also present, the diffusion is marked by multiple cycles of introduction, withdrawal, and reintroduction. This period is commonly referred to as the ‘era of ferment’ (Anderson & Tushman, 1990). The stage is characterised by complex interplay between a company, its potential customers, its suppliers, and its competitors. The phase ends when a standard for a service or product is established.
In the following, final phase, the market stabilisation phase, a dominant design has been established, ending the era of ferment, and improvements to the service or product are mostly incremental. The diffusion trajectory can generally be visualised with a single diffusion curve,

which is commonly S-shaped. In this final phase, companies often strive for large profit margins or large market shares. The phase ends when the dominant design is substituted (and sales thus drop), for instance by a new breakthrough technology.
An overview of the pattern of development and diffusion of applications is shown in **Figure 2.5.1.1**.

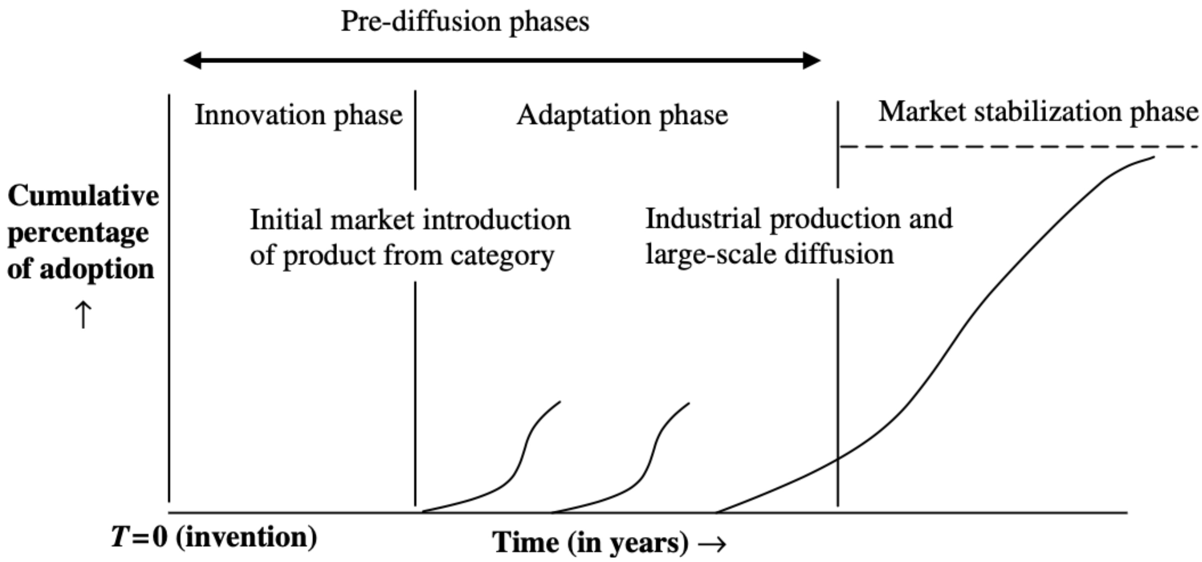

Figure 2.5.1.1. A schematic overview of the pattern of development and diffusion of applications. Reprinted from Ortt (2010).

Uncertainty, as discussed in the previous section, is also prominently present in the pattern of development and diffusion. Two findings make this obvious. Firstly, the length of the phases. While for some technologies the innovation phase only lasts a few years, others need multiple decades before the first application is introduced to the market (Ortt & Schoormans, 2004). Next to this, different scenarios of the pattern can occur. The model namely assumes that every breakthrough (communication) technology goes through three subsequent phases. However, there are also technologies for which applications never diffuse on a large scale, not even after multiple decades, or technologies that start to diffuse on a large scale very shortly after their invention (and thus skip the adaptation phase almost completely).

The existence of three distinct phases in the development and diffusion of a breakthrough technology has several managerial implications.
Firstly, the phases show that, on average, it takes about two decades before a product or service that makes use of a breakthrough technology starts diffusing on a large scale. This lengthy period, among other things, could explain why many (small) companies have a hard time surviving this period due to cash-flow difficulties.
Supplementary, companies should be aware of the position of a breakthrough technology, diffusion-wise, at a certain point in time to be able to set up appropriate strategies. If a technology is still in the innovation phase, it makes no sense to adopt a market penetration strategy and go forward with one, and one only, form of a product or service. The uncertainty in the market as well as in the technology will most likely result in a cycle of introduction, withdrawal, and reintroduction. Betting on a single standard of a service or product will therefore make the firm very rigid to change and result in high exit barriers (Harrigan, 1980), enhancing the chance of failure.
Thirdly, different alliances need to be sought for in each phase. In the market adaptation phase a new market most likely needs to be discovered, altering current markets, customer needs, suppliers, etc. Alternatively, in the market stabilisation phase, when the uncertainties of the market adaptation phase have been resolved, companies often look to benefit from economies

of scale to ascertain large market shares and obtain considerable profit margins. To reach the differing objectives of the consecutive phases, different types of alliances should be pursued. Finally, the erratic nature of the adaptation phase also has a managerial consequence. As customers are unable to evaluate (part of) the product or service that implements a breakthrough technology, since they cannot cope with it yet, standard market analyses like consumer analysis, data analysis, and customer analysis (Armstrong, 2001; Taschner, 1999) cannot be applied effectively. This makes it extremely difficult to predict the market potential of an innovation that applies a breakthrough technology. Here again, uncertainty plays an important role.

2.5.1.1 The role of applications in the adaptation phase

At the beginning of the adaptation phase, the first product, process, or service that incorporates a breakthrough technology is presented. This first (working principle of an) application can be very determining for the further development of alternative applications that incorporate that breakthrough technology. The first demonstration of the digital camera in 1975 by Steven Sasson, an engineer at Eastman Kodak (Lucas Jr & Goh, 2009), for example, steered the development of applications that are based on the breakthrough technology of a light-sensitive cell to one direction. The interest of many others was sparked by this prototype, although the demonstration was also surrounded by a lot of scepticism. Businesses attributed noteworthy resources to the further development of digital cameras because of Sasson's demonstration. Instead of exploring alternative applications that rely on a light-sensitive cell, like, e.g., solar cells (Fraas, 2014), the primary focus of companies lied on improving image quality, resolution, and other features relevant to photography. This continuous development led to significant improvements in the camera industry, as digital cameras eventually even got incorporated into smartphones, but diminished the pace of development of other applications making use of light-sensitive cells. This example shows why it is so important to, before the fuzzy front-end of the NPD process, formulate the substitute possible applications for a breakthrough technology. It might be that other, perhaps even more promising, applications are overlooked by the tunnel vision created by the first introduced application. If the alternatives that can be thought of are known, profitability of companies can increase because a more thought-out decision can be made on which application to pursue.

2.5.1.2. Diffusion in the market stabilisation phase

One researcher that made a significant impact in the field of the diffusion of applications was Everett Rogers. He described diffusion of applications as the process where an innovation is communicated through particular channels, over a certain period of time, and adopted amongst the people that make up a social system (Rogers, 1962). The scientist revealed that if the degree of adoption is plotted over time, the so-called 'adoption curve' is often bell-shaped. Rogers showed that the adoption at first is slow, when only the innovators and early adopters embrace an innovation. Then, the adoption picks up pace as the early majority implements an innovation. Finally, the number of adopters reaches its maximum value as the late majority and the laggards join the user base of an innovation. Each of these five social entities have their own characteristics that businesses can make use of. The S-shaped diffusion curve and the five social entities that are fundamental to this curve are shown in **Figure 2.5.1.2.1** on the next page.

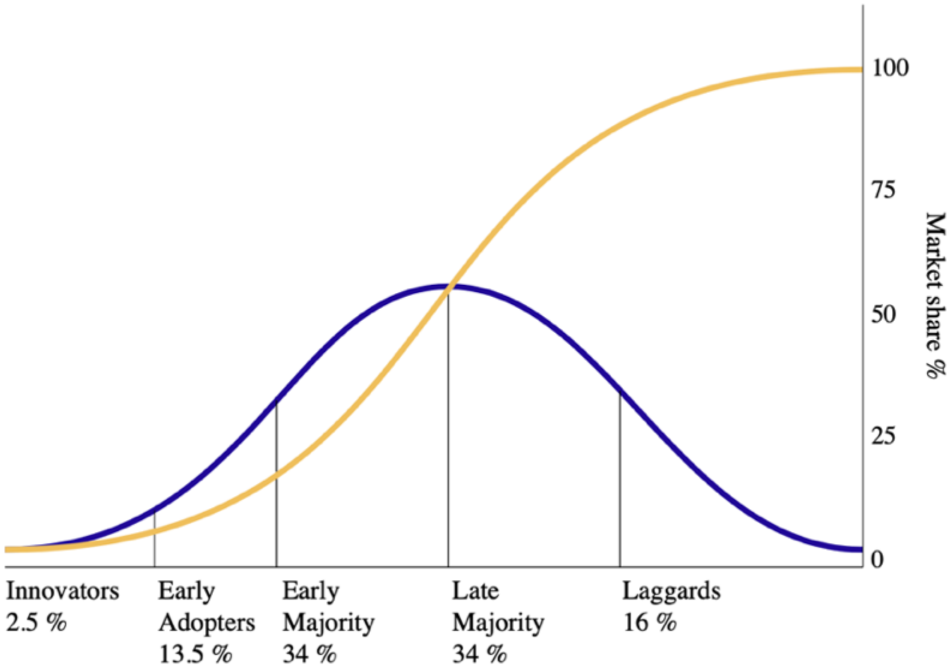

Figure 2.5.1.2.1. Diffusion as theorised by Rogers. The level of adoption is shown (yellow) is shown as well as the successive entities that cause the adoption. Based on Rogers (1962) but retrieved from Wikipedia (2023).

Note that, according to Ortt and Schoormans (2004), the narrative of Rogers is only applicable once an application has left the pre-diffusion phases and has entered the market stabilisation phase.

When moving from the early adopters to the early majority, Moore (1991) spots the existence of a so-called ‘chasm’. The scientist states that the early adopters are often technology enthusiasts that like to take risk and experiment with new products. However, the early majority lacks these two characteristics and will therefore most likely reject the innovation. This makes it hard for companies to diffuse their applications from the early adopters towards the succeeding social unit. To cross the chasm, Moore suggests that innovative companies need to focus on a specific market segment, or a ‘beachhead’, and develop a targeted marketing strategy that addresses the unique needs and preferences of that segment. Once the company has established a foothold in that market, it can then expand to other segments and eventually reach the broader mainstream market.
Figure 2.5.1.2.2 shows how the model of Moore builds forth on the model of Rogers, and how the pattern of development and diffusion is actually an extension to both of these models. Where Rogers proposed a smooth bell-shaped diffusion curve, Moore recognised a hurdle when moving from the early adopters to the early majority. Ortt explained this hurdle through an erratic process of introduction, withdrawal, and reintroduction cycles by adding the adaptation phase.

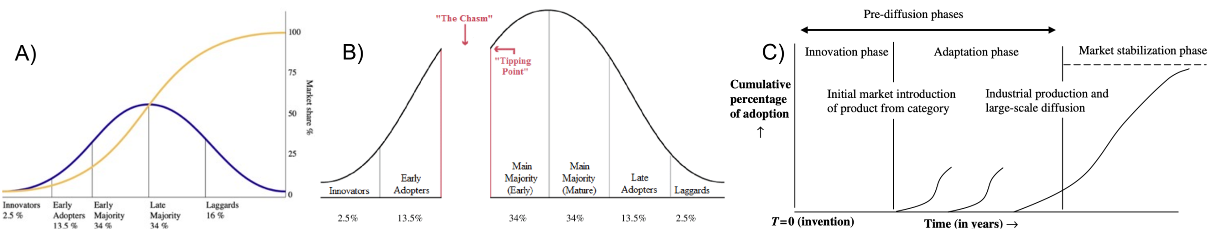

Figure 2.5.1.2.2. Diffusion as seen by A) Rogers, B) Moore, and C) Ortt. The three figures visualise that one model is an extension of the previous model when moving from left to right. Reprinted from A) Wikipedia (2023), B) Perkins (2015), and C) Ortt (2010).

2.5.2 Introducing applications

When innovative companies are developing an application, it can be fruitful if they can evaluate the status of this application. It makes sense to introduce the application on a large scale only when the application is situated at the end of the adaptation phase. To judge whether an application is 'ready' for large-scale introduction, multiple ways of analysis exist. One framework is that of Vik, Melås, Stræte, and Søraa (2021), who assess the status of an application by looking at a combination of readiness levels. Another methodology of evaluating the status of an application has recently been introduced by Ortt and Kamp (2022). The researchers developed a framework consisting of seven core actors that need to be in place before large-scale diffusion can take off. The seven core actors are supported by seven influencing factors that can explain why a core actor is or is not hindering large-scale diffusion. This framework is described in more detail in **Appendix 1: seven core actors** and **Appendix 2: seven influencing factors**.

After analysing an application, companies can decide to wait with market introduction or to go forward with it. This dubious phenomenon is described by *timing of entry*. Timing of entry refers to "the order of entry into a new or existing space (e.g., market, industry, or geographic region), relative to competitors, technology development, product life cycle, or other contextual referents" (Zachary, Gianiodis, Payne, & Markman, 2015, p. 1389). Timing of entry thus refers to the strategic decision of when to enter a market with an application. It is a critical decision for firms as it can have a significant impact on their success in the market. Entering too early can result in a lack of customer interest and inadequate infrastructure, while entering too late can mean that the market is already saturated with competitors. The timing of entry is influenced by a range of factors, including firm capabilities and resources, market prospects, modes of entry, and intentions, among others (Zachary et al., 2015).

If an innovative company decides to initiate diffusion of its application, it must choose a way of doing so. Manifold ways of introducing an application to the market exist. One example is the Expert Recommendations for Implementing Change (ERIC) list of implementation strategies (Powell et al., 2015). Another example is by making use of niche strategies. Introduction via niche strategies is also part of the framework of Ortt and Kamp (2022), which builds forth on the work of Ortt, Langley, and Pals (2013). Niche introduction strategies are explained in more detail in **Appendix 3: introducing applications**.

2.6 Quantum dots

This subsection explains the breakthrough technology central to this thesis, being that of quantum dots (QDs). This emerging technology is later on used to partially apply the framework for finding applications for a breakthrough technology to.

2.6.1 Metals, semiconductors, and insulators

Solid materials are commonly assigned to either one of three categories: metals, semiconductors, or insulators (Seitz & Johnson, 1937). For a more thorough, in-depth discussion on these materials, the reader is referred to books concerning the theory of solids, like, i.e., Li (2006).
Metals are comprised of a continuous set of energy levels, with half of them filled with electrons (commonly known as the Fermi level) and half of them empty at T=0 Kelvin due to the Pauli exclusion principle. The electrons in the occupied levels can easily be promoted to higher states, for instance by thermal excitation or by adsorption of a photon.
Semiconductors and insulators showcase a discontinuous set of energy levels. The levels filled with electrons, the valence band, and the levels deprived of electrons, the conduction band, are separated by a so-called bandgap. The bandgap is a region in the energy landscape that

cannot be occupied by electrons. Bandgaps of semiconductors are typically 0-5 electron volt (eV), while bandgaps of insulators are commonly larger than 5 eV. The electrons in the valence band can thus only be promoted to the conduction band if the amount of supplied energy of the source of excitation is equal to or larger than the width of the bandgap. This explains why semiconductors can conduct electricity, and why its large bandgap makes that insulators cannot. The most common semiconductor is crystalline silicone (Nebel, 2003), but semiconductors can also be composed of equimolar quantities of group Ⅲ and group V elements of the periodic table, or even elements of groups Ⅱ and Ⅵ of the periodic table. A schematic overview of the energy distributions in metals, semiconductors, and insulators is shown in **Figure 2.6.1.1**.

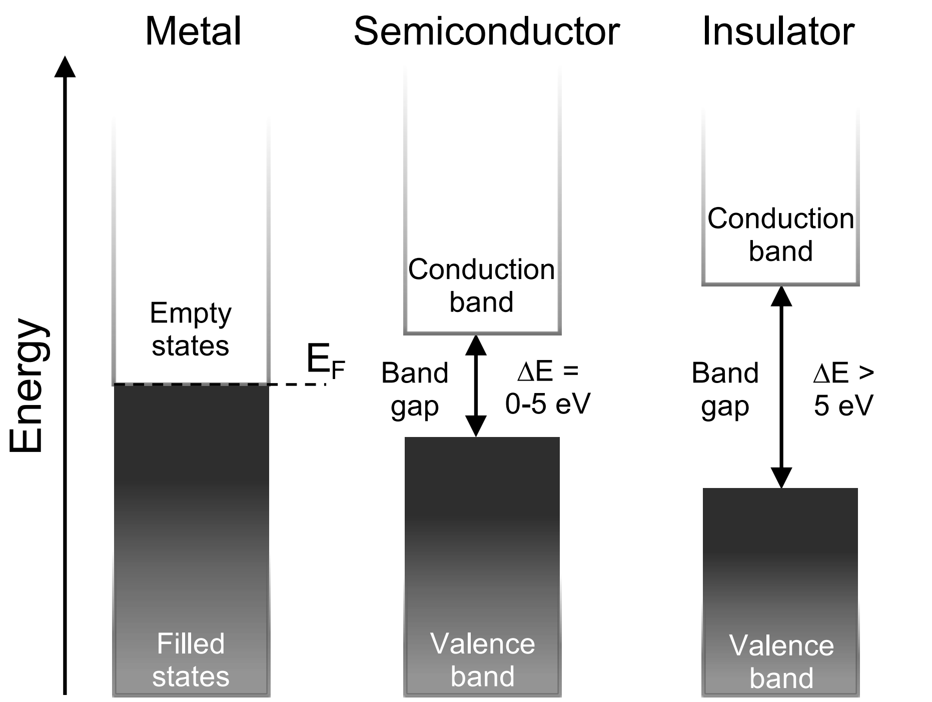

Figure 2.6.1.1. Band structures of metals (*left*), semiconductors (*middle*), and insulators (*right*). The Fermi level of metals is indicated with E_F.

2.6.2 Electron-hole recombination in semiconductors

When a negatively charged electron is promoted from the valence band to the conduction band, it leaves behind a positively charged void in the valence band, which is termed a 'hole'. The electron-hole pair together make up what is called an exciton. The electron can fall back from the conduction band to the valence band. When the hole and the electron meet, the exciton is annihilated. This phenomenon is known as (electron-hole) recombination. Three ways of recombination exist (Polese, 2021), and this is visualised in **Figure 2.6.2.1** on the next page.

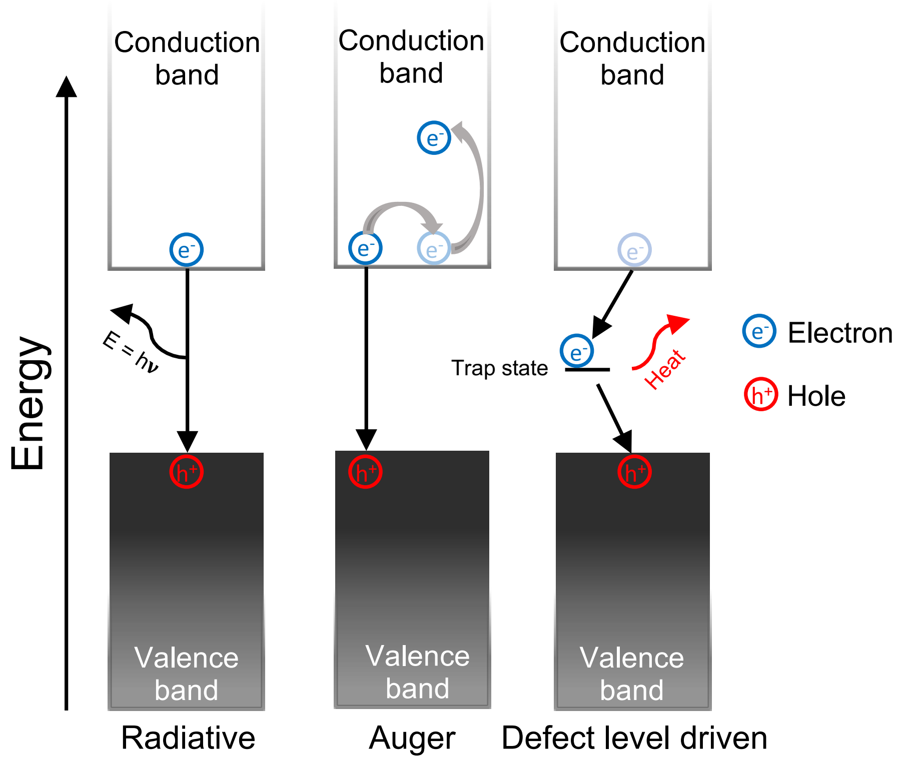

Figure 2.6.2.1. *Three sorts of recombination: radiative* (left), *Auger (middle), and defect level driven* (right).

In radiative recombination, a photon with energy equal to the bandgap is released. For Auger recombination, the electron passes its energy to an adjacent electron to promote it further into the conduction band. For the final type of recombination, also known as Shockley-Read-Hall recombination, interstitials, impurities, or vacancies in the lattice of the semiconductor introduce energy states within the bandgap. In a multi-step process, the energy is released non-radiatively in the form of thermal vibrations via these trap states. The thermal vibrations are called phonons and are absorbed by the lattice, resulting in heating of the lattice.
Radiative recombination is generally the preferred type of recombination.

2.6.3 Nanoscale semiconductors

As described by de Broglie, all particles (so also electrons) exhibit both particle-like and wave-like behaviour. The wave-like character of a particle can be described by a set of waves (termed wavefunctions), where each wavefunction represents a certain energy level of the particle. When the size of a semiconductor crystal is scaled down to the nanometre scale, the size of the crystal itself becomes comparable to the length of the waves (called the wavelength) that describe the electrons present in it. As the crystal becomes smaller, the electrons become more confined within it. The result of this confinement is that the distance between the energy levels of the wavefunctions becomes larger. Since the energy levels of the electrons are now separated by a larger distance, the width of the bandgap of the semiconductor is enlarged. Next to this, distinct energy levels form at the edges of the bandgap, rather than continuous energy levels as was the case in bulk semiconductors. This phenomenon is commonly known as quantum confinement. For a more exhaustive discussion of the quantum confinement effect the reader is referred to the particle-in-a-box model. The two resulting phenomena of quantum confinement (enlargement of the bandgap and formation of very distinct energy levels at the band edges) are shown in **Figure 2.6.3.1** on the next page.

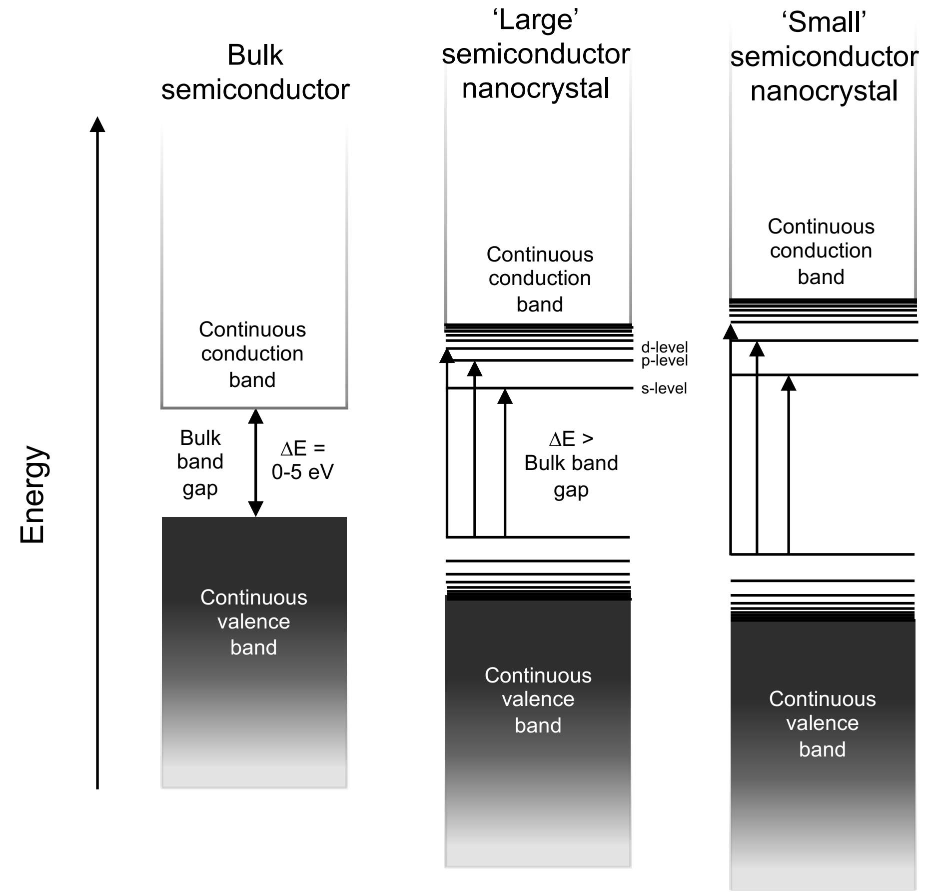

Figure 2.6.3.1. The band structures of bulk semiconductors (*left*), as well as nanocrystals of two different sizes (*middle* and *right*). The bandgap energy and the spacing between the distinct energy levels are larger for smaller nanocrystals than for bigger nanocrystals. The three arrows in the *middle* and *right* schematic visualise the S-, P-, and D- adsorption transitions, when an electron from a distinct energy level at the edge of the valence band is promoted to a distinct energy level at the edge of the conduction band. If this electron recombines with the hole radiatively, light of a very specific wavelength (energy) is emitted.

The width of the bandgap energy can thus be engineered by precisely controlling the size of nanoscale semiconductors. Since the energy levels at the edges of the band edges are now so well-separated, very distinct adsorption and emission energies become apparent. This means that the electrons can be excited into the conduction band with a very precise amount of energy (adsorption), and that a very monochromatic colour of light (light of a very specific energy) is emitted if the electron recombines with the hole again in a radiative manner (emission).

2.6.4 Quantum dots

The nanocrystals of semiconductors are commonly known as (colloidal) quantum dots (QDs) and are typically 2 – 10 nanometres in size (Wagner, Knipe, Orive, & Peppas, 2019). They are synthesised in ensembles and in solution through various methods like thermal decomposition methods, reduction, and nonhydrolytic sol-gel methods (J. Park, Joo, Kwon, Jang, & Hyeon, 2007). During these synthesis methods, particles are formed that do not all have exactly the same size. The more alike the sizes of the ensemble of particles are (described by a term called monodispersity), the narrower its emission and adsorption peaks are (because the energy landscapes of the particles within the ensemble are then more similar). After their synthesis, QDs are inherently unstable, as they contain many reactive surface atoms. The surface can be protected by passivating ligands that are retained on the surface during the synthesis procedure (Wood & Bulovic, 2010). Besides passivating the surface, the ligands also

solubilise the particles in dispersions. By picking appropriate ligands, stable colloidal dispersions in (a)polar solvents can be prepared. These dispersions can then be processed through various cheap, large area liquid-based deposition techniques, such as spin coating, drop casting, and inkjet printing (Shirasaki, Supran, Bawendi, & Bulović, 2012).
Although ligands can passivate most of the surface states, some remain. The residual dangling orbitals that are caused by these surface states can result in trap states (section **2.6.2 Electron-hole recombination in semiconductors**) that deteriorate the performance of QDs (since recombination is no longer radiative because of the trap states). Their photoluminescent quantum yield (PLQY), the number of photons emitted per excited electron, can drastically deviate from unity due to these trap states. Optimising the surface coverage of the QDs by the ligands can increase the PLQY. Another methodology that leads to increased PLQY is growing a shell (or multiple) of wider bandgap material around the core to passivate trap states. Extremely stable QDs with PLQYs nearing 100% are reported by making use of this synthesis procedure (Hines & Guyot-Sionnest, 1996; Lifshitz et al., 2006; Y. S. Park et al., 2011). A schematic of a core/shell QD with passivating ligands is shown in **Figure 2.6.4.1**.

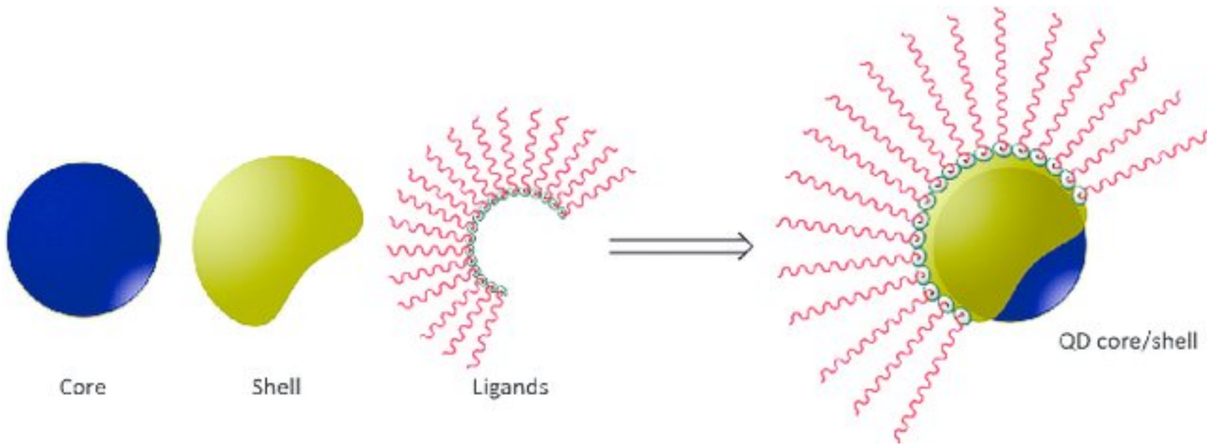

Figure 2.6.4.1. Schematic of the basic architecture of a QD that consists out of a core, a shell, and passivating ligands. Reprinted from Martínez and Kouznetsov (2016).

QDs exhibit unique optical and electronic properties like bright, stable, and tuneable fluorescence, narrow emission and adsorption spectra, and high quantum yield. These characteristics can be altered either through the shape and size of the nanocrystals (as discussed earlier), or by changing the composition of the QDs. The first phenomenon is visualised in **Figure 2.6.4.2** on the next page.

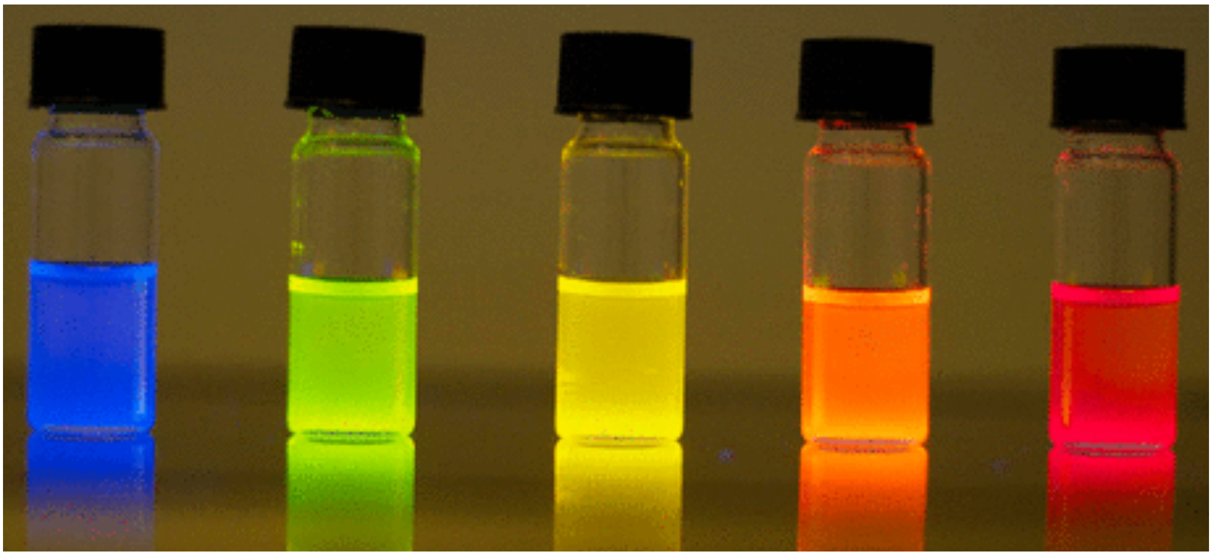

Figure 2.6.4.2. Quantum dots of the same material, CdSe/ZnS. Due the difference in size of the nanocrystals, photons of different wavelength are emitted upon excitation. Reprinted from Rogach (2014).

The most widely used QD to date is CdSe. However, some countries or regions, like the European Union, prohibit the use of CdSe in electronic products due to toxicity concerns ((EU), 2015). Therefore, alternative materials that potentially have a more benign nature are intensively researched, like e.g., InP (Brunetti et al., 2013) or QDs made of carbon.

In conclusion, QDs are a tool that can be used to solve problems or facilitate (new) products. The particles are an example of one of the smallest units of analysis within the field of nanotechnology, and therefore they can be regarded as a technology. Next to this, the technology is rather new (its discovery dates back to the 1980s (Bawendi, Steigerwald, & Brus, 1990)). The technology has the potential to drastically increase the price-performance ratio of existing products and processes, or even result in new product classes. As of now, it is not evident what can be done with the technology and whom the technology might be utilised by. Therefore, the technology is a *breakthrough* technology. This makes QDs a suited and interesting candidate for validating how and which applications for a breakthrough technology can be found. Due to their diverse properties, QDs can be imagined to be the underlying technological principle behind many, diverse innovations and applications.

3. Research methodology

This chapter describes the main methods that will be used to achieve the research objective and answer the research questions that are stated in section **1.3 Research objective and research questions**. The main methods of use will be a literature review and verification of the composed framework by partially applying it to a case. The former will be used to discover possible methods for finding applications for a breakthrough technology and establish the factors that are determining in this process. The methods and factors will then be combined, and the resulting framework will be partially applied to the case of quantum dots to evaluate how possible applications for a breakthrough technology can be found. The principles behind the two methodologies that seem suited for answering the research questions are explained in more detail below.

3.1 Literature review

The research questions in this proposal are mainly explorative in nature. This means that no sound theoretical basis is present, yet, and that the current research aims at gaining a deeper understanding of the subject at hand. A literature review can aid in discussing a certain matter and constructing a new theoretical framework (Snyder, 2019).
Snyder (2019) identifies three types of literature review: systematic, semi-systematic or narrative, and integrative or critical.
Systematic literature reviews are the standard in literature reviews (Davis, Mengersen, Bennett, & Mazerolle, 2014). Based on prespecified inclusion criteria, a systematic literature collects and analyses data from existent research and/or identifies and assesses relevant research. Its aim is to collect all recorded evidence to answer a particular research question.
Semi-structured or narrative literature reviews are meant for topics that are investigated by multiple research groups from divergent disciplines (Wong, Greenhalgh, Westhorp, Buckingham, & Pawson, 2013). Next to reviewing a topic, a narrative literature review also seeks to investigate how a topic has developed over time.
Integrative or critical literature reviews are the rarest type of literature review. They aim to develop new perspectives and theoretical frameworks through assessing, critiquing, and synthesising literature on a research topic (Torraco, 2005). This type of literature review typically lays hands on either new, emerging topics or on mature ones. For the latter, the integrative literature review aims to review knowledge bases, and review, reconceptualise, and expand existing theoretical foundations. For the former, the goal of the critical literature review is to create preliminary theoretical models and conceptualisations.
The literature review will compose of four consecutive phases (Snyder, 2019).
In the first phase, the approach to the literature review is designed. Search terms must be determined, as well as in- and exclusion criteria. On top of this, the appropriate databases need to be specified.
Next, the literature review is conducted. It might be wise to test, adapt, and retest the designed approach before starting the literature review.
During the successive phase, the conducted review is analysed. A standardised procedure must be set up on how to retrieve data from each article systematically.
Finally, the findings of the literature review need to be documented.

Jesson, Matheson, and Lacey (2011) recognise that before starting a systematic literature review, it might be wise to do a scoping review. Scoping includes the activities of the first phase as described by Snyder (2019), but additionally aims to investigate what is known about a subject, what the research gaps are, and how much relevant material is obtainable. One outcome of scoping can be the localisation of all domains that say something about a certain topic. Therefore, scoping is also known as mapping. Scoping thus takes one step back and considers all the relevant research topics that mention something noteworthy about a particular subject. After all these domains are known, a systematic literature review can be conducted on each of them.

Based on the above, a non-structured literature review was first conducted to help understanding and/or defining the core constructs that are needed for comprehending this thesis. This literature review aided in answering research questions 1.1 and 1.2, which asked how a (breakthrough) technology and an application can be defined. These two questions are research questions that consider terminology.
Then, a systematic literature review will be performed to find out what methods of finding applications for breakthrough technologies are present and suited. This systematic literature review will be preceded by a scoping review. A mind map will be drawn to establish all fields of research that are relevant for finding applications for breakthrough technologies. Once the appropriate fields of research are known, these fields will form the input for the search terms of the systematic literature review. This literature review will help in answering research question 1.3, which questioned which methodologies for finding applications for breakthrough technologies are existent. An overview of this systematic literature review is given in **Table 3.1.1**

Table 3.1.1. Overview of the systematic literature review set up to discover methodologies for finding possible applications for a breakthrough technology.

	Included	**Excluded**
Document type	Reviews and articles in peer-reviewed journals Book chapters	Patents Presentations Work-in-progress documents
Year of publication	1990 – 2023	Pre 1990
Language of the article	English	Other languages
Search terms present in title, abstract, or keywords	"Breakthrough tech*" OR "emerging tech*" AND "applications" OR "finding applications" OR "new product development"	Other search terms
Subject area	Business, management, and accounting	Other subject areas
Databases	Scopus for the articles and book chapters and Google Scholar for the review papers	Other databases
Citations	>20	<20

This literature review considers reviews and articles in peer-reviewed journals and book chapters. These records are chosen because they seem most appropriate for finding frameworks for formulating applications for a breakthrough technology. The literature review looks into methodologies presented between 1990 and the beginning of 2023. Reasons for this time range are twofold. Firstly, the current way of approaching the NPD process is expected to be rather new (and therefore it makes little sense to elongate the time range). Secondly, the number of records that need to be analysed becomes larger if a wider time window is chosen. Only records written in English are considered because most scientific literature is either written in English or translated into English. The chosen search terms are the resultant of the scoping review. Business, management, and accounting is chosen as subject area because the problem statement central to this thesis concerns how the NPD process can be *managed* better. Scopus is chosen as database because of user experience. Google scholar is chosen to find the review articles because Google scholar has an option to select only review articles in the advanced search menu. Finally, only records that are cited more than twenty times are considered. Considering records with fewer citations will increase the set of records significantly because there are many records that are only cited a few times.

This criterion does, however, result in the exclusion of potentially relevant records that have just been published and are therefore not yet cited often.
After this review, a second systematic literature review will be carried out to uncover factors that are determining in the process of finding possible applications for breakthrough technologies. This literature review will not be proceeded by a scoping review, and aims at answering research question 1.4, which questioned what factors influence the process of finding applications for a breakthrough technology. The design of this systematic literature review is given in **Table 3.1.2**.

Table 3.1.2. Overview of the systematic literature review set up to discover factors that are of importance in the process of finding possible applications for a breakthrough technology.

	Included	**Excluded**
Document type	Reviews and articles in peer-reviewed journals Book chapters	Patents Presentations Work-in-progress documents
Year of publication	1990 – 2023	Pre 1990
Language of the article	English	Other languages
Search terms present in title, abstract, or keywords	“barriers” OR “factors” OR “parameters” AND “important for” OR “determining” AND “finding applications” OR “new product development”	Other search terms
Subject area	Business, management, and accounting	Other subject areas
Databases	Scopus for the articles and book chapters and Google Scholar for the review papers	Other databases
Citations	>20	<20

The reasoning behind the choice of the criteria of this literature review coheres with the reasoning provided for the literature review designed for finding methodologies for formulating applications for a breakthrough technology.

3.2 Verification of the framework by applying it to a case

To evaluate the framework formulated in the current work, it must be applied to a certain case. The case should be a breakthrough technology, that has the potential to be applied in numerous applications but of which it is still unsure what the technology can do and whom the technology might serve.

The case that the formulated framework will be partially applied to in the current thesis project is that of quantum dots. As verified in section **2.6.4 Quantum dots**, QDs are a breakthrough technology. QDs were first discovered in the 1980s (Bawendi et al., 1990). Nowadays, there are multiple applications that have been introduced to the market, for instance QD-based televisions. However, there are no QD-based applications that currently dominate the market and have diffused on a large scale. Therefore, QDs are presently situated in the adaptation phase. It is not yet exactly clear how QDs can be incorporated into applications and whom these applications can serve.
Sections **1.4 Scientific and managerial relevance** and **2.6.4 Quantum dots** explained why it is scientifically as well as managerially relevant to take QDs as means of example. Applying the framework to this specific example illustrates a struggle that every breakthrough technology faces in its early days; how can one find possible future applications for an emerging technology of which it is hardly known what it can do and whom it might be useful for? This emerging technology is thus fit to evaluate the framework for finding applications for a breakthrough technology that is constructed in the current work.

4. Frameworks and factors

This section synopsises the results of the two literature reviews. Research questions 1.1 and 1.2, considering the definitions of (breakthrough) technology and application, are answered in sections **2.1.1 Defining technology** and **2.2 Breakthrough technology**, and **2.3 The trio of breakthrough technology, innovation, and application**, respectively. The resultant definitions are therefore not recurring in the current section. Here, the results kick off with an overview of the found frameworks for finding applications for breakthrough technologies and the factors that are of importance in this process. Then, the found frameworks are compared to each other based on the discovered success factors.

4.1 Frameworks for finding applications for breakthrough technologies

The development of the number of records during the literature review to discover existent methodologies for finding possible applications for breakthrough technologies, as elucidated in section **3.1 Literature review**, is shown in **Table 4.1.1** below.

Table 4.1.1. Development of the number of records as the search for existent methodologies for finding applications for a breakthrough technology was refined.

Steps	Remaining number of records
Search terms	18,097
Limit to reviews, articles, and book chapters	8,265
Limit time range to 1990 - 2023	8,107
Limit to English	7,862
Limit to business, management, and accounting	535
Limit to >20 citations	143
Limit to relevant papers	28

The literature review resulted in 143 papers in Scopus and three review articles in Google Scholar. The abstracts of the literature present in this set of papers and reviews were read and if seemed relevant, a paper or review article was analysed with greater effort. Eventually, 28 articles and one review were read in-depth.
The literature review yielded zero frameworks that come up with a list of possible applications for a breakthrough technology, with application and breakthrough technology as I define the terms. However, five frameworks that could be important in reaching this goal were discovered. These are summarised in the following five subsections.

4.1.1 Framework 1: the TAS framework

Terzidis and Vogel (2018) designed a unified model for the technology push process. It consists of four consecutive phases, complemented by Technology Readiness Levels (TRLs), as can be seen in **Figure 4.1.1.1** on the next page.

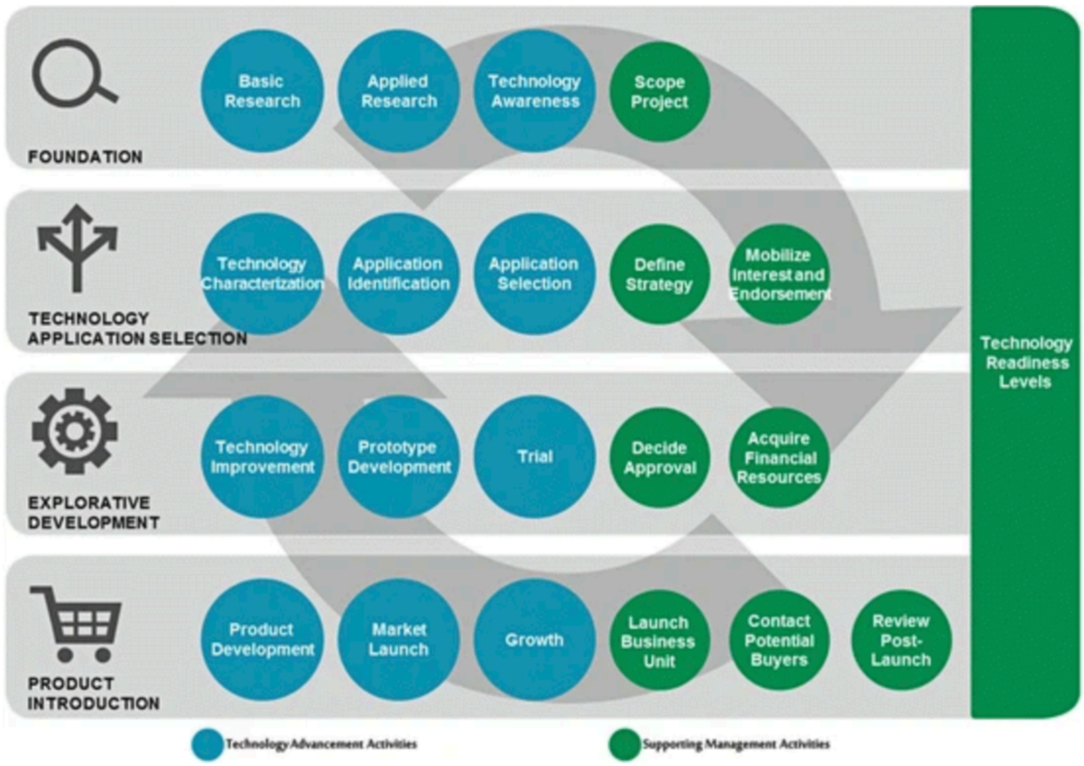

Figure 4.1.1.1. A consolidated model of the technology push project. Reprinted from Terzidis and Vogel (2018).

The second phase, the technology application selection phase, is the phase that relates to the problem sketched in this thesis. To reach the goals of this phase, characterising a technology, subsequently formulating a set of possible applications, and finally picking the best ideas, Terzidis and Vogel constructed a Technology Application Selection (TAS) framework. The framework consists of three sequential phases. The authors identify multiple approaches to reach the goals of each phase and pick the best-suited approach in each phase. The framework is designed in such a way that it can be implemented in workshops. The workshops should be carried out in teams, each consisting of at least three and not more than five members. The individuals of the teams should have diverging backgrounds. The TAS framework is summarised below in **Figure 4.1.1.2**.

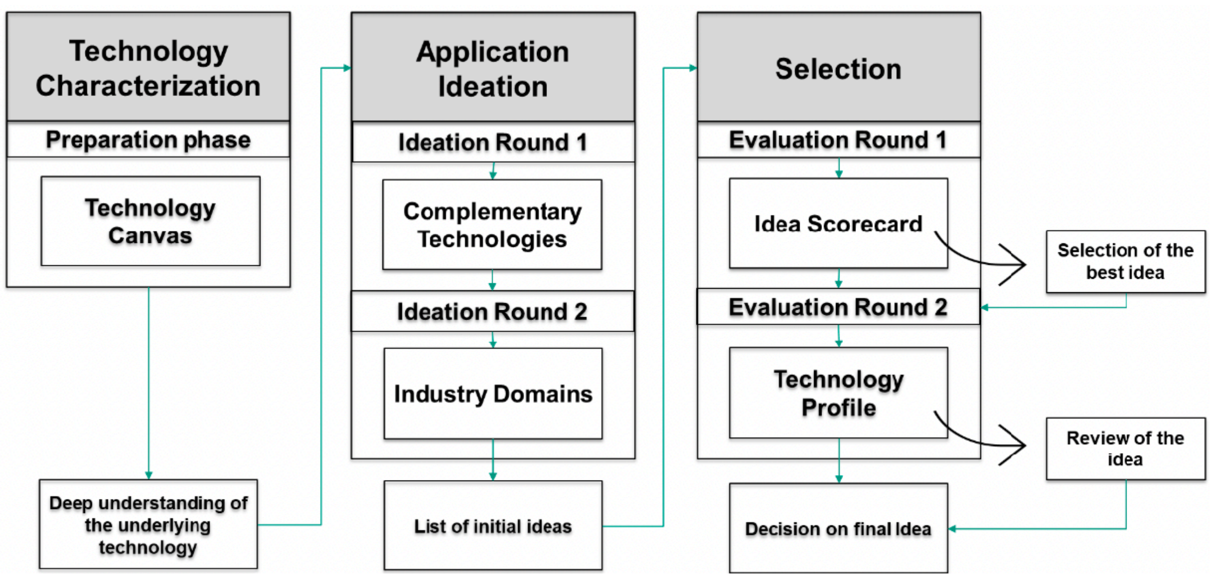

Figure 4.1.1.2. The three phases of the TAS framework. The figure includes sub steps within and outcomes of each phase. Reprinted from Manthey, Terzidis, and Tittel (2022).

Before the first phase, the technology characterisation phase, an expert introduces the technology and its most important aspects to the teams. Then, the teams gather, and a set of questions is discussed to characterise the technology by tracking down its most important information. This results in multiple technology canvases and the canvases are discussed among groups to grasp a common understanding of the technology. The questions fundamental to a technology canvas are shown in **Table 4.1.1.1**.

Table 4.1.1.1. The constructs and questions that form the technology canvas (Terzidis & Vogel, 2018).

Construct	Question
Name	What is the technology called?
Problem	What problem is solved by the technology?
Technology description	What is the main idea and how does it solve the problem?
Technology benefits	What are expected benefits of the technology?
State of the art	What are current solutions for the problem? What are alternatives?
Drawing	How can the functionality of the technology be depicted?
Technical novelty	What makes the technology unique? How is it different from the state of the art?

In the second phase, the application ideation phase, ideas of possible applications for the emerging technology are generated. This is done in two rounds. The first round is composed of a trend analysis (Henkel & Jung, 2009) and the second round is made up of brainstorming given industries (Nelson, 2005). These sessions are conducted in the form of a knowledge café. In a knowledge café setting, the trend analysis and brainstorming are performed in groups, and the groups rotate in rounds. The number of rounds depends on the time available. During the trend analysis, groups are presented with a stimulus at each station of the knowledge café. A stimulus consists of a technological trend. The stimulus is presented by a headline with a short description and a few pictures. Based on this stimulus, groups formulate possible applications, without judgement. During the successive brainstorming rounds, the stimuli are based on industries that could benefit from using the technology. At the end of the second phase, each station is discussed, duplicate ideas are disposed of and ideas are grouped, and the best 15-20 idea clusters are selected by the groups for the evaluation phase. In the final phase, the generated ideas are evaluated, and the most promising ones come forward. Actors need to shift their focus from diverging towards converging. All ideas are presented as an application proposal. The evaluation is done in two rounds. In the first round, the idea scorecard is used to carry out a broad screening. The idea scorecard is constructed through evaluating the applications on a set of questions, which are written down in **Table 4.1.1.2**. The applications are rated based on the idea scorecard. The top ideas, which depend on the number of groups participating in the workshop, are then further analysed. Each group works on one idea.

Table 4.1.1.2. The evaluation factors and accompanied questions that make up the idea scorecard (Manthey et al., 2022).

Evaluation factor	Question
Technical feasibility	Is it technically possible to realise a product?
Market potential	Is there a market of sufficient size to create a business?
Profitability	Does the product have a chance of being profitable?
Team values fit	Do we have the right attitudes, resources, competencies, and commitment?
Market entry	Are there any crucial market entry barriers to overcome?

In the final step, the Technology-Utilization-Model (TUM) (Hartelt, Wohlfeil, & Terzidis, 2015) is implemented to assess the remaining, most promising applications in depth. Lead users of the potential applications are asked to put forth evaluation criteria, called the technology profile. Then, the applications, and alternative applications, are assessed based on the technology profile. The applications are ranked, and the most promising application can be taken to the explorative development phase of the technology push project.

Framework 1 involves teams with divergent backgrounds to spark creativity. However, the exact composition of the teams is not specified. The technology is introduced to the teams by a technology expert, but it is not clear how the expert does this. Then, a set of questions is answered to better understand the technology. These questions are, however, basic. Ideas for possible applications are then generated through trend analysis and brainstorming workshops, both structured through a knowledge café setting. These applications are not synchronised with the definition as provided in this thesis. Finally, the applications are also assessed. This lies, however, not in the scope of the current research project. Framework 1 makes use of multiple qualitative methods to formulate applications for a breakthrough technology. Quantitative methods are not relied upon.

4.1.2 Framework 2: a 3-step CTA approach

van Merkerk and Smits (2008) developed a 3-step Constructive Technology Assessment (CTA) approach and applied and evaluated it to lab-on-a-chip technology to find medical applications that build on the technology. The approach helps actors to deal with the absence of transparency among parties that are involved around the development of a technology and the high level of uncertainty surrounding the development of emerging technologies.

In the first step, actors are invited and informed. The CTA analyst first decides which actors to reach out to. van Merkerk and Smits (2008) state that a heterogenous set of actors, including both insiders and outsiders to the technology, should be selected. The third step in the procedure namely consists of a dialogue workshop and a mixed group of actors tends to look at the technology from a broader perspective, rather than focusing on technical issues. Actors that can be thought of are SMEs, insurance companies, lead users, policy makers, scientists, etc. If an actor agrees to participate, the CTA analyst informs the actor on the technology at hand. One way to do this is by sending two 3-page documents. One document explains the scientific advances and the other document lays out the history of the technology, including the actors that got involved over time. These two documents can be based on an extensive literature research and on interviews. The actors are expected to read the two documents as preparation for the next step.

During step two, the CTA analyst has individual interviews with each actor. In the interview, the analyst asks questions about different topics (e.g., sociocultural, technical, political, economic) and what these topics will look like for this technology in a certain moment in the future. By doing this, the analyst sketches different scenarios together with the actors. The scenarios are analysed by the CTA analyst and the main differences between the scenarios are used as starting point for the third step.

In the third step, the actors come together in dialogue workshops. In the first two workshop rounds the differences between the scenarios are discussed. Then, a brainstorming session follows aimed at diverging the ideas even further and coming up with potentially even more scenarios. In this third round, the actors need to come up with technology options, which is an application combined with a specific practice or market. In the fourth, final round, the technology options are converged again by assessing the scenarios on desirability and feasibility. The alternatives are scored with a prioritisation matrix to yield the most feasible and desirable outcomes.

Framework 2 involves a divergent set of actors. Although suggestions for actors are made, the exact composition of the set of actors remains unclear. An analyst guides the process. The actors are informed by the analyst, based on a literature review and interviews. Both of these methods are not specified, and the documents that are composed based on the literature review and the interviews might be hard to understand for actors that are outsiders to the technology. The group discussions that follow are structured by first interviewing each actor individually. During the group discussions, technology options for a breakthrough technology are formulated and assessed. The technology options are close to, but not the same as, an application as defined in the current work and the assessment of the alternatives lies out of the scope of the present thesis project. Multiple qualitative methods are incorporated, but quantitative methods are not used.

4.1.3 Framework 3: integrating vision assessment into CTA

Where van Merkerk and Smits (2008) used individual scenarios followed by dialogue workshops, Roelofsen, Broerse, de Cock Buning, and Bunders (2008) integrated the Interactive Learning and Action (ILA) approach with vision assessment to deal with emerging technologies. Both papers recognise the need for some form of prediction of the future surrounding an emerging technology to be able to discuss the possible benefits and drawbacks of applications incorporating the technology with a heterogenous set of actors. Roelofsen et al. (2008) develop, evaluate, and discuss their framework by applying it to the field of ecological genomics. Ecological genomics are defined as “the application of genomics techniques in the field of (soil) ecology in order to enhance our understanding of ecosystem function” (Roelofsen et al., 2008, p. 334). The framework developed here thus assesses the possible future (dis)advantages of using genomics techniques in (soil) ecology. The emerging technology of genomics is in this case already steered towards applications in the field of (soil) ecology. Although the unit of analysis here is already one step narrower than coming up with (and analysing) potential applications for a breakthrough technology, the framework could still be useful for finding applications for an emerging technology.
The authors state that experts, being the developers of the technology, should form the basis for formulating future visions of the technology, since public awareness is limited in the case of ecogenomics. These experts are united in a consortium.

The early status of the emerging technology is verified in the first step. Around twenty semi-structured interviews are conducted with several actors outside of the consortium (i.e., policy makers, industry, NGOs, etc.).
In the second step, the literature, being (review) articles, is reviewed regarding developments around the emerging technology. This literature review should yield some future applications of the technology.
Thirdly, around twenty members of the consortium are interviewed semi-structurally. Questions are asked about their research within the consortium and their relation to topics that the literature review mentioned. Next to this, their reason for participating in the consortium is discovered, as this may relate to their future expectations of the technology. Outlooks of future developments in the field of the technology are asked for. Finally, the interviewees are asked which applications surrounding the technology they expect in the future, what the potential (dis)advantages of these applications might be, and whom the applications might affect.
Then, focus groups are set up. Here, members of the consortium are brought together and interact to gather insights and produce data rather than focusing on a question – answer format (Morgan, 1996). The focus groups aim at exploring ideas about the future of the technology. Two groups of seven consortium members are formed, and the sessions each last four hours. The interviews and the literature review can give domains that the focus groups can discuss. The discussions are led by an experienced moderator, notes are taken by an assistant, and the sessions are recorded and transcribed. After possible future scenarios are discussed within the focus groups, six steps are undertaken to finally result in a table that lists participants' ideas, as shown in **Figure 4.1.3.1** below.

5	2	1	3	4
Alternatives	**What is measured?**	**Applications**	**End users/ End benefits**	**Losers**
		Detection agriculture		
		Detection nature		
		Spin-offs		

Technical elements ⟷ Contextual elements

Figure 4.1.3.1. Example of a scheme that lists ideas coming from the focus groups. Reprinted from Roelofsen et al. (2008).

In the final step, concrete images of the future are assembled. The results of the preceding steps are analysed on four aspects. These being the current technical knowledge existing, the objectives of the different applications, the contexts in which the applications will be used (distinguishing direct and indirect contextual factors), and assumptions that the future visions build on. By doing this, most relevant information surrounding future scenarios and possible applications of an emerging technology can be gathered.

Framework 3 recognises that experts should form the basis of formulating applications for a breakthrough technology, because public awareness is low. The only experts that are involved in the framework are, however, experts on the technology itself that are united in a consortium. The early status of the technology is verified first through twenty interviews. There are, however, simpler methodologies for checking whether a breakthrough technology is still in the innovation phase, e.g., by looking if there are applications that rely on that technology that have been introduced to the market. Then, a literature review and semi-structured interviews form the basis for focus groups, led by a moderator, where applications for a breakthrough technology are formulated. Clear directions for the interviews are given, but no details on the literature review are provided. The outcomes of the focus groups are documented very carefully, which can be fruitful in such extensive, in-depth discussion sessions. Concrete images of the future are composed, but these are not the same as applications as described in the current thesis. Again, various qualitative practises are used, but quantitative approaches are absent.

4.1.4 Framework 4: the TeknoRoadmap framework

Bildosola, Río-Bélver, Garechana, and Cilleruelo (2017) combined quantitative and qualitative methodologies in a framework, called the TeknoRoadmap (TKRM) framework, to obtain an all-encompassing depiction of breakthrough technologies. Quantitative and qualitative methods are combined because they can complement each other's shortcomings. The quantitative part of the framework is made up by bibliometrics, which is in actuality more a research field than a methodology en sich. Explicit bibliometric methods that are namely used are data mining (web content mining and text mining) and trend analysis. Additionally, the framework incorporates a semi-quantitative method in the form of technology roadmapping (TRM). The qualitative part of the framework consists of expert assessment. The framework relies on two phases and encompasses eight steps. The outcome of the framework is twofold: a research activity profile and a technology roadmap. An overview of the framework is shown in **Figure 4.1.4.1**.

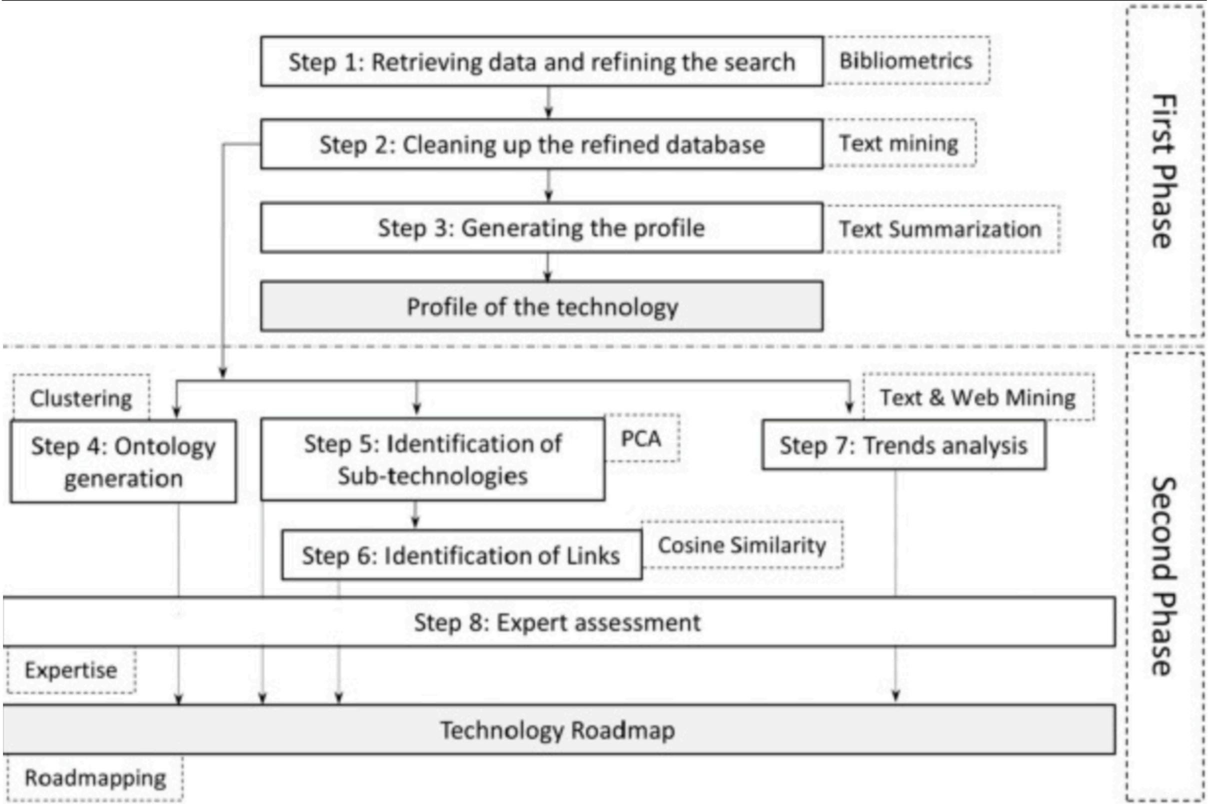

Figure 4.1.4.1. An overview of the TeknoRoadmap framework. Reprinted from Bildosola et al. (2017).

In their paper, Bildosola et al. (2017) apply the framework to cloud computing (CC) but mention that the framework can be used for any kind of emerging technology. The framework is explained below.

The tasks of the first three steps are carried out using the text mining tool software of VantagePoint. Two databases are generated by repeating the first two steps twice. One database is filled with documents that concern specific applications of the emerging technology, whereas the second database contains documents, being scientific publications, concerning the technology's basic research. The databases will be used in steps 4 – 8.
In step 1, a database is constructed that holds scientific publications that are directly connected to the technology that is analysed. Scientific databases like Scopus and Web of Science (WoS) can be used, and the search can be refined through setting a time range and making use of Boolean conditions (connecting keywords or phrases with the operators "AND", "OR", and "NOT").
During step 2, the generated database is cleaned up by making use of some of the basic functionalities of a text mining tool. The scientific publications of step 1 are integrated into a single database, and so-called 'fuzzy matching' is applied to keywords, affiliations, and author's names. This implies, for example, searching for synonyms of keywords and looking for different ways of spelling or abbreviating author names and affiliations. The text mining tool groups the outcomes that mean the same thing (synonyms, acronyms, plural forms, etc.) under a single word. Recall that steps 1 and 2 are performed twice to generate an application database and a basic research database.
In step 3, the profile is generated. This profile is made up of two parts: one part concerns the state of the research on the technology and its evolution, and the other part holds a research community profile and a literature profile. The first part analyses the most increased and the most used keywords. The latter part generates an indication of research activity in the form of

auto-correlation maps, co-occurrence maps, and top-ten lists of conference or journal publications, institutions or authors, top countries, and the government, academic, or private publication distribution. At the end of this step, the profile of the technology is formed.

The technology profile is then exploited in the upcoming, second phase.
The two databases that were the resultant of step 2 are used as input for step 4. The main goal of step 4 is constructing an ontology for the technology and formulating an ontology for the applications of the technology. In other words, the hierarchical structure of the technology and the applications, including its main fields, is generated. The CC application ontology is shown in **Figure 4.1.4.2** below. The technology ontology of CC is not shown for clarity.

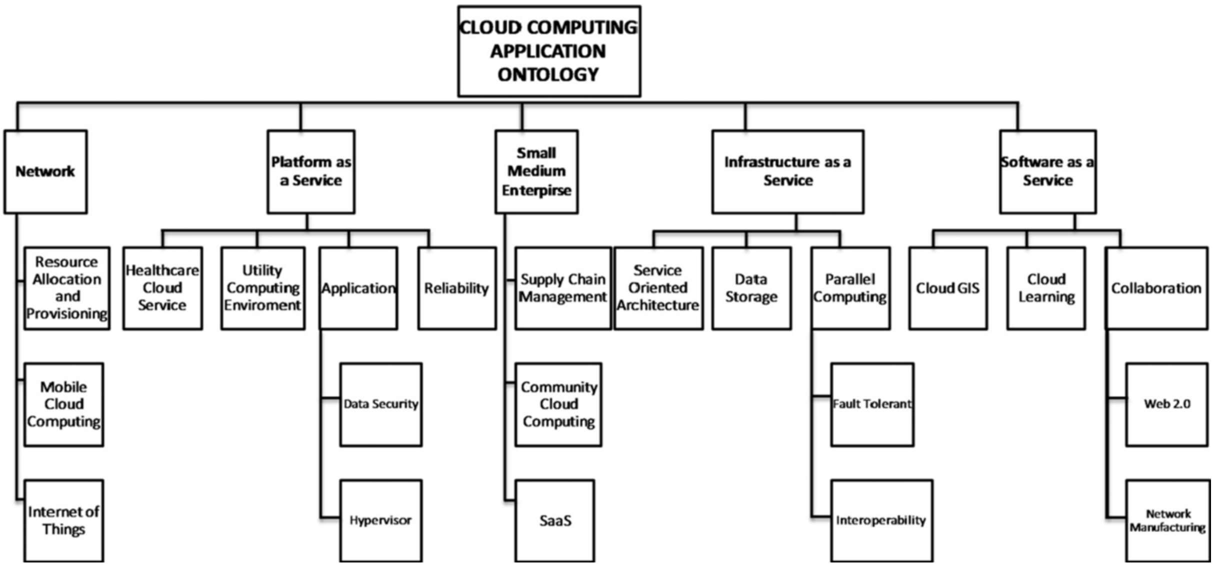

Figure 4.1.4.2. Overview of the CC application ontology. Reprinted from Bildosola et al. (2017).

The ontology is designed by, iteratively, going through four consecutive steps, which are explained below.

(1) *Generation of a co-occurrence matrix*. Again with the aid of VantagePoint, the most important and relevant keywords are discovered. Keywords that only occur less than three times and keywords with a too general meaning are excluded from the list.
(2) *Generation of a distance matrix*. The co-occurrence matrix is used to generate a distance matrix. The distance matrix is based on a similarity measure being Salton's cosine. The co-occurrence matrix is therefore exported to R software and the distance matrix was constructed in R by programming the selected measure calculation. The distance matrix describes how dissimilar sets of keywords are from each other.
(3) *Clustering*. The distance matrix is used to identify similar keywords and cluster them. The Agnes package of R, with the Ward clustering approach, was selected. The resultant is a dendrogram that shows the hierarchy of the clusters.
(4) *Naming*. The terms appearing within the clusters are analysed and the cluster is named by the most representative term. The resulting terms are the main fields that appear in the ontology. The names that are given to the main fields, as well as the overall ontologies, need to be discussed with experts. Expert involvement is discussed in more detail in step 8.

In step 5, sub-technologies are identified. The two databases of step 2 are now divided into years. With Principal Component Analysis (PCA) the sub-technologies are identified per year. By making use of the Multidimensional Scaling (MDS) tool in VantagePoint, the sub-

technologies are placed on a map and their interrelations are shown. When the sub-technologies are identified, they need to be placed within a TRM. As the x-axis of a TRM depicts the time horizon, placing a sub-technology on this axis is straightforward. Placement on the vertical axis is, however, more cumbersome. The terms included in each sub-technology need to be analysed and placed on the corresponding main field. When sub-technologies concern the same concept, they are grouped into a unique sub-technology, lengthening the duration period of that sub-technology. The resultant of this phase is two TRMs: one of the technologies and one of the applications. The decisions taken in this step also need to be discussed with experts.
To find out which basic research activities have led to (important) applications, links between the sub-technologies in the technology TRM and sub-technologies in the application TRM are analysed in step 6. If no link between a sub-technology in the technology TRM and a sub-technology in the application TRM is found, this research field is either not suited to be developed into an application, or the research field has potential to be turned into an application (but this has yet to be discovered). The links are investigated through cosine similarity. The outcome is a value between zero and one, where zero means no link and one means total similarity. A threshold for acknowledging a strong link can be set. The code for establishing the links was developed in Python. Sub-technologies in the technology TRM that link with sub-technologies in the application TRM are given matching colours.
The most increased keywords that were the resultant of step 3 and the terms retrieved through a web content mining method are the inputs for step 7. In step 7, short- and medium-term future pathways of the technology are established and integrated within the TRMs that were generated after steps 5 and 6. The decisions made in this step need to be assessed by experts. Step 7 is split up into two parts: one trend identification is used for the short-term future and one trend identification is used for the medium-term future.
For the short-term future the time range lies between n and (n+1) years, where n is the year after the year wherein the research is conducted. The most increased keywords are used to identify plausible paths of the technology. The keywords in the list of year (n-2) are used to identify terms that need to be placed within year n of the TRMs. The keywords in the list of year (n-1) are used to locate terms that need to be put in year (n+1) of the TRMs. This resulted in 20 keywords for each year in the case of the CC analysis.
For the medium-term future the time range spans from (n+1) years to (n+3) years. The year (n+1) is thus made up by a conjunction of the short- and medium-term methods. The forecast in this part is surrounded by more uncertainty and web content mining is used to make predictions. The source of information comes from two types of web pages, being technology providers and market research companies. Several representative web pages of both categories need to be selected, and this selection needs to be discussed with experts. A web crawler is then used to extract text files from the web pages. The authors use the web crawler of the IBM Watson platform. However, this crawler was only used to crawl HTML content and to generate the text files. The text files were namely exported to and analysed in VantagePoint with Natural Language Processing (NLP). With NLP nouns that represent concepts are identified and lists with terms that are appearing frequently are constructed. The high frequency terms then need to supplement the existing TRMs, either within existing sub-technologies or within a new sub-technology, or should be placed within the ‘market’ TRM, where sub-technologies that have reached the market are shown.
In the final step, being step 8, interviews with experts are set up to discuss the decisions made in the previous steps. Decisions that need consideration are both of the ontologies that were generated, the constructed TRMs, and the selected web pages. In the case of CC, three expert interviews were set up, each lasting around one hour. The experts were highly specialised in the field of the technology but showcased low-level hierarchy.

The outcome of the eight steps for CC is shown in **Figure 4.1.4.3** on the next page.

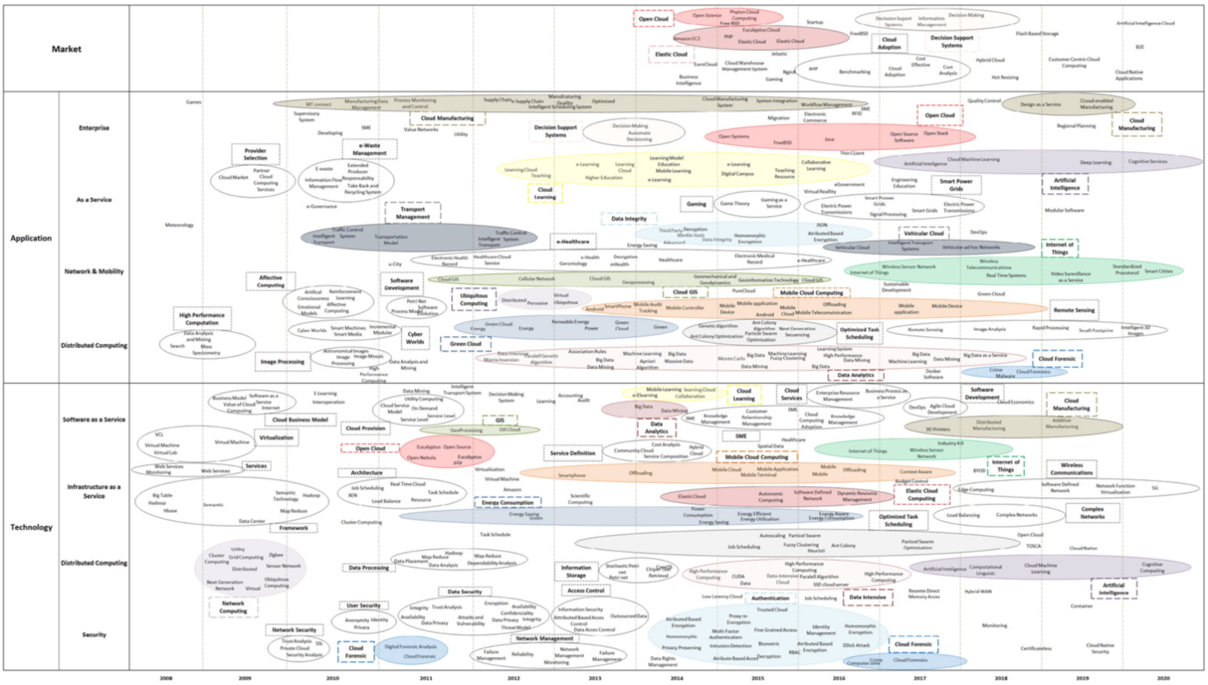

Figure 4.1.4.3. Overview of the CC TRM spanning from 2008 to 2020. Reprinted from Bildosola et al. (2017).

Framework 4 starts with generating a research activity profile. Although this profile is nice to have, it is not required to formulate possible future applications for a breakthrough technology. In contrast to the previous three frameworks, framework 4 combines quantitative methods with qualitative approaches. The quantitative methods are described (in more detail when compared to explanations provided in the previous three frameworks), but do require text mining software and programming knowhow. The qualitative part is present to a lesser extent as the only method used consists of retrospective expert involvement. One of the outcomes of the framework is a TRM as shown in the figure above. The TRM is made up of a technology part and an application part, and clearly shows which advances in basic research have led to which innovations. The sub-technologies, belonging to a certain main field, are, however, not applications as defined in the current work.

4.1.5 Framework 5: the framework of Zhou et al. (2019)

The final and most recent framework is that of Zhou et al. (2019). The authors revealed commercial applications and potential innovation pathways of solid lipid nanoparticles (SLNs), which are a breakthrough technology in the field of nano-enabled drug delivery. The researchers designed a framework to do so, combining expert judgement, TRM, and several text mining approaches, being net effect analysis, SAO technique, and term clumping. The framework is made up of eight steps, divided into three stages. The framework is summarised in **Figure 4.1.5.1** on the next page and its steps are explained below.

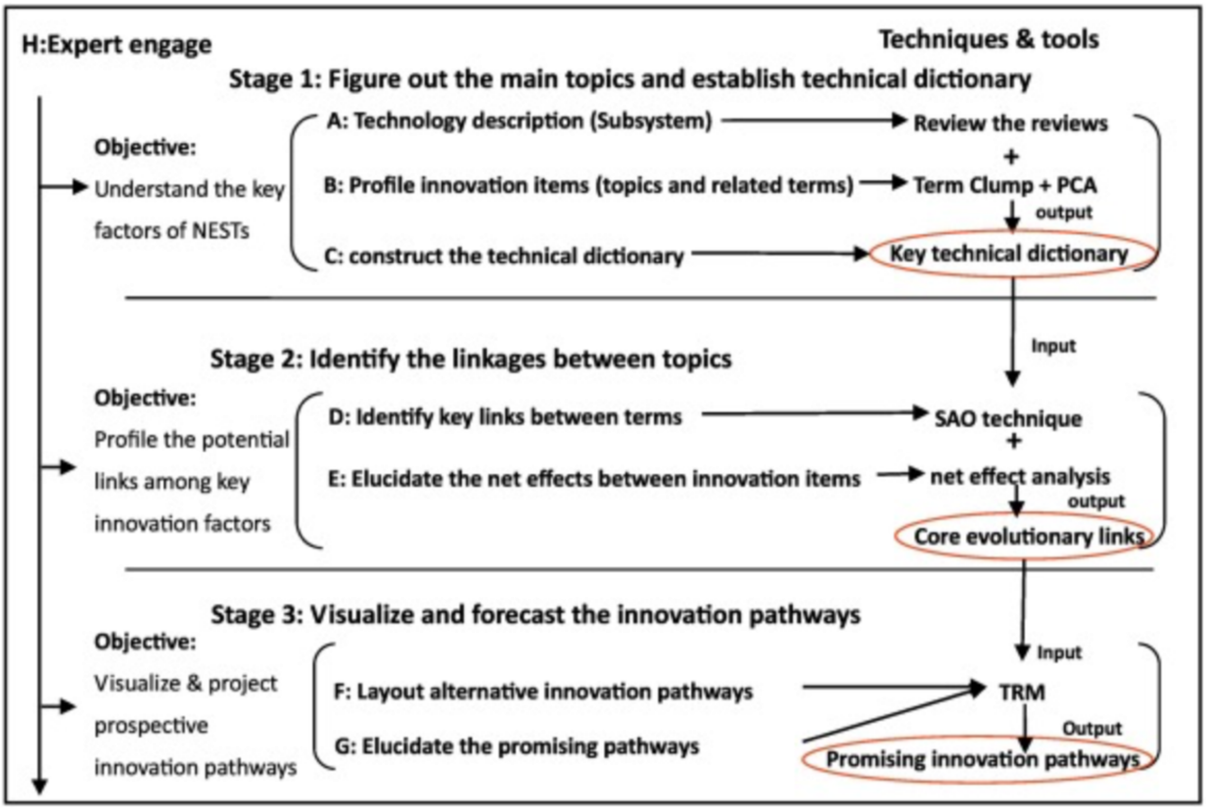

Figure 4.1.5.1. Overview of the framework of Zhou et al. (2019). Reprinted from Zhou et al. (2019).

As a first step, a set of (review) papers, patent records, and business-oriented news, reports, and working papers that relate to the technology is gathered.
For the (review) papers, WoS is used. The time range is set, and search strings are thought of. For each search string, 30 random abstracts are read. If more than 70% of the abstracts are related to the technology, the search string is accepted.
For the patent records, the same search strings and selection criterion are used. The patent database can for instance be the Derwent Innovation Index (DII).
For the reports, working papers, and business-oriented news, the search strings were entered into the commercial database ABI/Inform.
The time range for the three SLN searches was 2000 – 2016.

Out of this set of (review) papers, patents, and records, the technical dictionary is constructed. The set is first imported into VantagePoint. Then, by making use of its natural language processing (NLP) system, nouns and noun phrases are extracted. By using term clumping, the set of nouns and noun phrases is reduced. A selection of this reduced set, i.e., the 500 most frequently used terms, are further analysed by experts. Involved experts either have expertise in the field of the emerging technology, or are text mining specialists. The experts can further reduce the set of 500 terms by getting rid of less interesting and general terms. This procedure is carried out for the three types of documents.
Next, PCA tools in VantagePoint, as well as manual assessment by the experts, are exploited to identify and cluster groups of terms that occur together more often than pure chance would designate. The result is a manageable number of clusters that denote topics regarding the breakthrough technology.
These topics then need to be allocated to certain subsystems of the emerging technology. This is in analogy with constructing an ontology in the TeknoRoadmap framework. To find out the subsystems, review articles are reviewed. The review articles are gathered from the search strings used in WoS, and can additionally be collected from search strings in WoS concerning a broader topic to keep the search less biased towards certain applications. Through implementing selection criteria, the set of review articles is reduced. The clusters that were

found earlier, together with their terms, are then assigned to the found subsystems. This classification is called the technical dictionary.

The terms present in the technical dictionary are consecutively analysed with the Subject-Action-Object (SAO) technique. Goldfire Innovator software is used for this purpose. Using this methodology, a subject, being the phrase or noun that represents the emerging technology, is linked to an object, which is the phrase or noun that represents the problem that has been solved or the old technology, by an action, being a verb (phrase) that shows how to solve the problem. The approach emphasises the relationship between two technologies, giving researchers handles to deal with the evolution of a breakthrough technology. The SAO software is used to construct SAO structures. The structures are reduced by the experts by deleting too general or meaningless structures. The SAO structures that hold the same subject and object, but differing actions, are grouped. The actions within the groups are then analysed as well as classified by their net effect, being either an increase (a positive effect), decrease (a negative effect), or just group usage. Verbs (phrases) are assigned to the three types of actions. By analysing the SAO structures, evolutionary pathways of the breakthrough technology can be recognised. To visualise this outcome, to establish the interrelations between the core research entities, and predict the future for the emerging technology, a TRM must be generated.

A TRM graph is composed of a horizontal axis and a vertical axis. The horizontal axis depicts a time range and the vertical axis, as assessed by the experts in the case of the SLNs, is made up of development stages (basic R&D, technology transfer, and commercialisation). The topics belonging to the subsystems that are found earlier are attributed to one of the development stages that makes up the y-axis. The placement on the x-axis is determined by first publication date for articles, application date for patents, and release date for commercial reports. The resulting technological evolution, in the case of SLNs, is shown in **Figure 4.1.5.2** below.

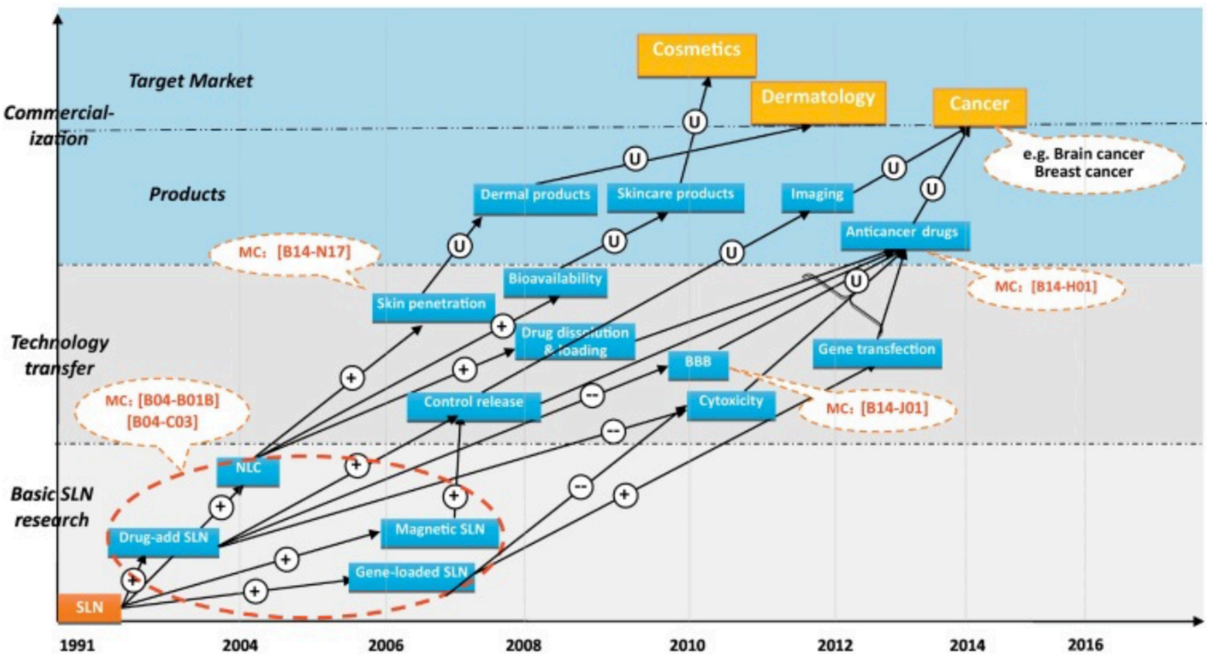

Figure 4.1.5.2. TRM for SLNs. Reprinted from Zhou et al. (2019).

As can be seen in the above figure, the TRM only runs until the present. It does not provide any forecasting of potential future innovation pathways of the emerging technology. To supplement this prospective vision, a workshop with a collection of experts can be organised. The outcome of the workshop is a multi-path mapping. The multi-path mapping for SLNs is shown in **Figure 4.1.5.3** on the next page.

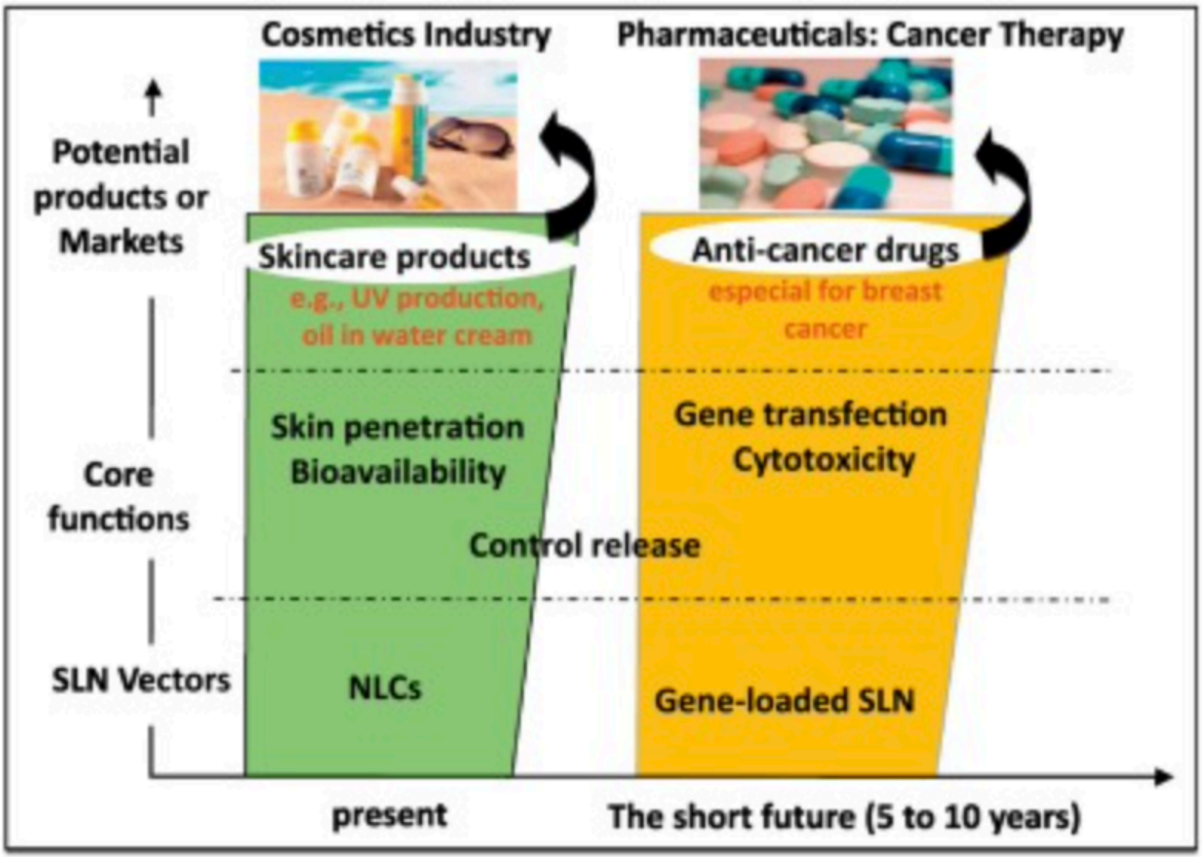

Figure 4.1.5.3. Multi-path mapping outcome of the expert workshop in the case of SLNs. Reprinted from Zhou et al. (2019).

Framework 5 has much similarity with framework 4. The text mining, however, not only relies on academic literature, but also takes patents and informal documents into account. The image of the technology created is therefore more all-encompassing. Next to this, the experts are involved in a continuous manner, rather than only at the end of the framework. The TRM that is created during the framework, however, only runs until the present and does not look into the future. Also, no applications, as I define the term, are generated in the TRM. To compensate for the lack of a future view in the TRM, a multi-path mapping is complemented, but this mapping is rather basic.

4.2 Factors influencing the process of finding applications for a breakthrough technology

The development of the number of records during the literature review to discover factors that are of importance in the process of finding possible applications for breakthrough technologies, as elucidated in section **3.1 Literature review**, is shown in **Table 4.2.1** below.

Table 4.2.1. Development of the number of records as the search for factors that influence the process of finding applications for a breakthrough technology was refined.

Steps	Remaining number of records
Search terms	145
Limit to reviews, articles, and book chapters	104
Limit time range to 1990 - 2023	103
Limit to English	98
Limit to business, management, and accounting	61

Limit to >20 citations	26
Limit to relevant papers	0

The systematic literature review that was set up to discern factors that are of importance in the process of finding possible applications for breakthrough technologies resulted in 26 papers and zero review articles. The abstracts of the papers were scanned and, if considered relevant, the papers were read in more depth. Out of the 26 papers, zero papers were deemed useful. This could be expected, as an all-encompassing framework that yields possible applications for a breakthrough technology, with the definitions as I provided them, is non-existent. Only some of the five framework papers of section **4.1 Frameworks for finding applications for breakthrough technologies** mentioned factors that are of importance *in their specific framework*.

As stated above, no factors that are of importance during the process of formulating possible future applications for a breakthrough technology could be discovered through a systematic literature review. The analysis and discussion of the term breakthrough technology and the five discovered frameworks can, however, give indications for factors that can be important in the mentioned process.
Firstly, there are some characteristics that the breakthrough technology that is central to the analysis must adhere to. For starters, it must not be *obvious* what the technology can do, how it can be used, or whom it could serve. Logically, if these three determinants are already obvious, it makes no sense to formulate a list of possible future applications for the emerging technology. An example of such a situation would be the discovery of a new medicine. It would then already be clear what the technology can do, in which products, services, or processes it can be incorporated, and whom the technology might be useful for. This factor is actually already embedded in the definition of a breakthrough technology as provided in section **2.2 Breakthrough technology**. Extending on this, the breakthrough technology must still be in the innovation phase. Next to the fact that the function of the technology, the applications it can be incorporated in, and potential customers should not be obvious, these factors should be *unsure*. Therefore, no applications that rely on the breakthrough technology should be introduced to the market. If some applications are already existent, the NPD process surrounding the breakthrough technology has already been initiated and particular pathways are already locked in (Collingridge dilemma). In this situation it already becomes clearer what the technology can do, in which applications it can be incorporated, and whom the technology can serve. If this is the case, it is no longer appropriate to formulate a list of possible future applications for the breakthrough technology.
Then, there are also some remarks to make about the process of finding applications for a breakthrough technology itself. Firstly, this process should combine qualitative and quantitative approaches in a balanced way. The methodologies can then support each other's shortcomings. Next to this, experts should be involved in a continuous manner. Experts can provide unique insights and expertise that are crucial for developing a list of applications for a breakthrough technology, because public awareness is low, and the emerging technology is surrounded by a lot of uncertainty (especially technological uncertainty). By involving the experts continuously, the process of finding applications for a breakthrough technology can be steered as it develops. It should be clear which experts to engage, and when to involve them. Additionally, the process should look into future pathways of the technology rather than only analysing it until the present (one of the differences between the TRMs of frameworks 4 and 5). By looking into the future, the formulation of possible *future* applications for a breakthrough technology is made possible. Finally, the process should conclude with the formulation of a list of concrete possible future applications of the breakthrough technology.

The characteristics that the breakthrough technology of analysis must showcase and the factors that are of importance in the process of finding applications for a breakthrough technology are summarised in **Table 4.2.2** on the next page.

Table 4.2.2. Characteristics that the breakthrough technology that a list of possible future applications is being formulated for must showcase and the factors that are of importance in this process.

Characteristics of the breakthrough technology
Functionality, incorporation in applications, and potential customers must be non-obvious
Functionality, incorporation in applications, and potential customers must be unsure
The breakthrough technology must be in the innovation phase
Factors of importance for the process of finding applications for a breakthrough technology
Using qualitative approaches and quantitative methods in a balanced way
Including experts in a continuous manner
Taking a look into possible future pathways of the breakthrough technology
Formulating concrete possible future applications for the breakthrough technology

4.3 Comparing the five frameworks

In this section, the five frameworks are compared to each other. The frameworks are compared on five success factors that appeared to be relevant for the process of finding applications for a breakthrough technology as discussed in the final paragraph of the preceding subsection. These factors include how the frameworks incorporate qualitative and quantitative measures, how they involve experts, how they look into the future and how they formulate applications for a breakthrough technology (as I define an application). The findings of this comparison are displayed in **Table 4.3.1**.

Table 4.3.1. Comparison of the five frameworks based on five success factors.

	1	2	3	4	5
Qualitative measures	Trend analysis and brainstorming workshops that are structured through a knowledge café setting	Individual interviews and a dialogue workshop	Semi-structured interviews and focus groups that are led by a moderator and are being recorded and transcribed	Experts on the technology are involved at the end of the process	Continuous expert involvement and a workshop
Quantitative measures	X	X	X	Text mining including basic research as well as applications	Text mining based on scientific literature, patents, and informal documents
Expert involvement	Technology expert informs teams that have a diverse composition	CTA analyst informs (based on a literature review and interviews) a group of actors that are insiders	Twenty members of the technology consortium are involved	Technology experts are interviewed at the end	Technology experts and text mining specialists are continuously involved

		as well as outsiders to the technology			
Looking into the future	Trend analysis and brainstorming is used to identify possible applications	In the dialogue workshops technology options are generated	Concrete images of the future are generated in the focus groups	A TRM is constructed that looks into the short- and medium-term future	A multi-path mapping is fabricated that looks into the short-term future
Formulation of applications (as I define it)	X	X	X	X	X

Looking at the table above, frameworks 4 and 5 overall embed most of the success factors. Upon comparing the two frameworks, the TRM of framework 4 is judged to be more in-depth and also looks into the possible future pathways of the breakthrough technology, rather than analysing it until the present (as is the case for framework 5). Therefore, this framework will be used as the basis for composing an adapted framework that is suited for finding applications for a breakthrough technology. However, framework 4 also has its shortcomings when looking at the goal of the current thesis project. What these weak points are and how they are resolved, sometimes by incorporating fragments of the other frameworks, is discussed below.

Firstly, framework 4 starts off with positioning the breakthrough technology. Although it is nice to know the evolution of the research on the technology, how the numbers of publications evolved, and which institutions were involved over time, to give examples of data collected in the first phase, this knowledge is not needed for formulating possible future applications for a breakthrough technology.
Secondly, framework 4 combines quantitative and qualitative measures, but the quantitative measures are more dominant than the qualitative measures. Additionally, the quantitative measures are described on a very basic level, which makes it hard to reproduce this part of the framework. Next to this, only academic papers are used in the text mining, whereas I believe that extending this dataset with patents and informal documents, as done in framework 5, yields a more overarching view of the breakthrough technology. Also, the qualitative measure is solely the retrospective involvement of expert, whereas I believe it is better to keep the experts involved throughout the whole framework to steer the process continuously. It is also not entirely clear which and how many experts must be involved.
Finally, framework 4 (actually, none of the frameworks) does not result in the formation of a list of possible future applications for the breakthrough technology. To reach this goal, the qualitative measures that are more strongly present in frameworks 1 – 3 can be looked at. In this way the use of qualitative approaches and quantitative methods becomes more balanced. For instance, the resulting TRM can be used as input for individual semi-structured interviews between an interview expert and a group of insiders and outsiders to the technology. When the TRM is formed, fields where the breakthrough technology can be applied become apparent. Based on these fields, it becomes clear who the insiders and the outsiders to the technology are. The results of the interviews can then be used as a basis for workshops, where the set of formulated ideas are first diverged before being converged. If all members of the workshops agree on the possible short- and medium-term future pathways of the technology, they can together formulate concrete possible future applications for the breakthrough technology. This thus means thinking of a functionality with subsystems that incorporates the breakthrough technology and that serves a customer group with a certain preference in a particular usage context for each future pathway. After the concrete possible future

applications are gathered, the alternatives can be assessed. This is, however, out of the scope of the current framework.
The steps of framework 4, and how each step should be adapted to overcome the shortcomings of the framework, are summarised in **Table 4.3.2** below.

Table 4.3.2. The steps that form framework 4 and how these steps can be adapted to overcome its shortcomings in formulating a list of possible future applications for a breakthrough technology.

Step	Framework 4	Adaptation
1	Retrieving data and refining the search	Patents and informal documents are added as data sources
2	Cleaning up the refined search	-
3	Generating the profile	Research profile is not retrieved. Only two literature profiles are gathered: one considering basic research on the technology and one regarding applications of the technology
4	Ontology formation	-
5	Identification of sub-technologies	-
6	Identification of links between the sub-technologies	-
7	Trends analysis	-
8	Expert assessment	Composition of the set(s) of experts is clarified as well as when to involve the experts to make sure they are continuously engaged during the process
9	-	The resulting TRM is used as input for qualitative methods to formulate applications for the breakthrough technology

The steps of the framework that is the resultant of the adaptations of framework 4 are elaborated upon in detail in the next section.

5. A ten-step framework for finding applications for a breakthrough technology, partially applied to quantum dots

In this section, a ten-step framework that can be used to find possible future applications for a breakthrough technology is proposed. This framework is based on the comparison of the five frameworks found, as described in section **4.3 Comparing the five frameworks**. This comparison was based on the success factors found in section **4.2 Factors influencing the process of finding applications**, which are in turn based on the discussion of the five frameworks. Framework 4 was judged to be best-suited for reaching the objective of this thesis, and was therefore taken as the basis of the ten-step framework. The shortcomings of framework 4 in relation to the goal of the current thesis project, and how the other frameworks are used to circumvent these limitations, is summarised at the end of the preceding section in **Table 4.3.2**. After the ten-step framework is described in detail in the following subsection, it is partially applied to the case of QDs in subsection **5.2 Partially applying the framework to quantum dots**.

5.1 Ten-step framework

This subsection describes a ten-step framework for finding applications for a breakthrough technology.

Step 1: Compose groups of experts.
The first group is preferably composed of two or three experts on the technology itself, for instance being researchers and developers that are actively working on the breakthrough technology.
Next to this, one or two text mining professionals are needed to assist in the text mining procedures. The first two groups should not be too big, since they will need to be continuously involved and this is hard if the groups are too big. Next to this, I expect that the marginal input of more of these types of experts will be very limited.
For the final part of the framework, one person that specialises in conducting semi-structured interviews and (leading) group discussions is needed.
Finally, a few experts that are insiders as well as outsiders to the technology (e.g., the earlier found technology experts, governmental representatives, policy makers, players from relevant industry sectors, insurance companies, environmental experts, etc.) are needed. In line with the reasoning of van Merkerk and Smits (2008) and Terzidis and Vogel (2018), it is important that the last group of experts has diverse competencies, to spark creativity, but is not too big, to structure the discussions. Based on the TRM that is the outcome of step 9, it becomes apparent in which fields the breakthrough technology can possibly be applied in the future. These fields can help reshape the search for relevant experts, especially the search for actors/partners in relevant industry sectors.
The expert groups will be consulted in different stages of the process. As Roelofsen et al. (2008) state, lead-users should not be involved, as public awareness is low and the possible future applications of the breakthrough technology are only known at the end of the process. They should, perhaps, be involved at the assessment of the alternative applications, which is not part of the current framework.

Step 2: Create a dataset containing academic literature that concerns basic research on the breakthrough technology. Examples of suited databases are Scopus and Web of Science (WoS). Supplement this dataset with patents and informal documents coming from society (think of, i.e., newspapers, websites, and blogs). An example of a patent database is the Derwent Innovation Index (DII), and the informal documents could be retrieved from ProQuest (former ABI/Inform). By combining these three types of records, the academic research on the breakthrough technology is incorporated, as well as business activity and developments that

are closer to society. The datasets are thus more all-encompassing than only including, for instance, academic literature.
The time range should run from n-3 to n years, with n being the year that the research is conducted. This range is chosen for multiple reasons. Firstly, by keeping the range small, the datasets stay manageable. Secondly, this time range only includes recent literature, excluding older, perhaps already irrelevant, literature (although older, perhaps relevant, literature is excluded by this time range). Finally, a longer time frame would be interesting for mapping the development of the breakthrough technology from its discovery until the present. However, the goal of the current framework is otherwise; the current framework should rather be used to predict the future. The past is, although being interesting, less relevant for the goal achieved by the current framework. The search terms and their Boolean refinements are discussed with the experts on the technology.

Step 3: Import the dataset into text mining software. An example of text mining software is VantagePoint. Next, refine the dataset. Start with removing duplicate records (records with identical titles and abstracts). Then, refine the keywords by making use of fuzzy matching and a Thesaurus tool. Fuzzy matching reports terms that mean the same but are spelled differently under one term. The Thesaurus tool can be used to group different words that refer to the same concept under one term (for example, ‘car’, ‘vehicle’, and ‘automobile’ are all clustered as referring to a car). The dataset refinement is discussed with the text mining expert(s).

Step 4: Extract the most frequent keywords and the most increasingly used keywords from the dataset. The most frequently used keywords are not used further, but they can help understanding what the technology is about. This is especially useful to inform the experts that are outsiders to the technology. The most increasingly used keywords can be extracted from the most frequently appearing keywords. The dataset should start at n-3, because the most frequently appearing keywords from this year are needed to calculate the most increasingly used keywords for year n-2. The most increasingly used keywords of years n-2 and n-1 will later on be the input for making predictions about the short-term future pathways of the breakthrough technology. The list of most frequent keywords and most increasingly used keywords is discussed and refined with the technology experts.

Step 5: In this step the foundation of the TRM is built.
First, generate a co-occurrence matrix of the author’s keywords in the text mining software. The author’s keywords are chosen because these keywords best indicate what a record is about. Next to this, comparison of keywords in VantagePoint is more accurate than for instance comparison of abstracts, because VantagePoint considers each full abstract as one argument (and thus does not look at the *content* within the abstracts). The co-occurrence matrix shows which keywords tend to occur together. Reduce the matrix by only including terms that occur at least three times and by excluding terms that either make no sense or have a too general meaning. Discuss the formation of the co-occurrence matrix with the technology experts and the text mining expert(s).
Extract the matrix to programming software (e.g., R or Python) and construct a distance matrix through using a similarity measure (i.e., the indirect Salton’s cosine). The distance matrix shows how alike keywords are regarding their co-occurrence within the records. Then, cluster the keywords that are similar (for instance by making use of the Ward clustering method within the Agnes package of R) and give names to the clusters. Discuss these programming steps with the text mining experts and the technology experts. The text mining experts can aid in the programming steps, and the technology experts can assist on the design of the ontology. The outcome of this step is namely a *technology ontology*, where the first layer depicts the *main fields* of the technology. They serve as a vertical breakdown of the TRM.

Step 6: Repeat steps 2 - 5 but then for records that concern applications that make use of the breakthrough technology. The result is a second ontology, namely the *application ontology*.

Step 7: Now that the vertical breakdowns of the TRMs are constructed, the TRMs need to be completed with horizontal breakdowns. For this purpose, *sub-technologies* are identified. With the aid of Principal Component Analysis (PCA), the datasets are divided into years and the sub-technologies are identified year by year. PCA namely establishes how often terms occur together in a set of records. Once the sub-technologies are found, they are placed within the TRMs. Placement on the horizontal axis is straightforward, as each sub-technology is located on the corresponding year. Vertical placement is more complicated. The terms within the sub-technologies are analysed to place them on the corresponding main field. Sub-technologies that represent the same construct are merged. The steps within this step are discussed with the text mining experts.

Step 8: The sub-technologies from the previous step are now analysed to identify links between the sub-technologies of the technology layer and the sub-technologies of the application layer. By doing this, it can be visualised which basic research led to which application. Absence of such a link hints that certain basic research cannot be transformed into an application, or that this transformation has yet to be discovered. For each sub-technology, the keyword-vector is constructed. Then, by programming a cosine similarity, for example in Python, links are discovered.

Step 9: By now, the TRMs are constructed from year n-3 until year n. In the current step, the possible short- and medium-term future pathways are gathered. Since the future of a (breakthrough) technology is highly uncertain, it remains questionable whether the methodologies presented below are actually appropriate for predicting the future of a breakthrough technology. The methods are, however, one way of giving researchers tangible handles for making predictions about something that is so uncertain.
To discover the possible short-term future pathways of the breakthrough technology, being years n+1 and n+2, the lists of most increasingly used keywords that were the resultant of step 4 are used. For the year n+1, the most-increased keywords of year n-2 are used, and for the year n+2, the most-increased keywords of year n-1 are used.
To discover the possible medium-term future pathways of the breakthrough technology, being year n+2 until year n+4, web content mining is used. Web pages of technology providers and market research companies are used as input. The selection of web pages is discussed with experts on the technology. A web crawler is then used to extract text files containing information that is present on the web pages. An example of a web crawler is IBM Watson. The text files are then extracted and imported into text mining software, where they are analysed with a Natural Language Processing (NLP) technique to extract high frequency terms. These terms are then placed on the TRMs. Together with technology experts, it is decided whether a found term belongs to an existent sub-technology, or makes up a new sub-technology.
Now that it is clear in which fields the technology can possibly be applied in the future, actors/partners related to those fields (especially the ones from industry) can be contacted to be included in the following, final step.

Step 10: In this final step, the created TRMs, and the steps taken to construct the TRMs, are used as input for discussion sessions.
First, the (group) discussion expert has one-on-one semi-structured interviews with the actors within the last group of experts.
Hereafter, the outcomes of these interviews (and thus the differences spotted by the interview expert) are used as input for two workshops. In the first workshop, the (differences in) opinions about the future pathways of the technology are investigated and together the list of possible future pathways is adapted as deemed appropriate. In the second workshop, concrete applications for the breakthrough technology that relate to the possible future pathways are constructed. So, a functionality with subsystems that incorporates the breakthrough technology and that serves a customer group with a certain preference in a particular usage context is thought of for each future pathway. In this final step, it is important that the actors related to

the main fields have a determining role. They are aware of the challenges in their field, and they can best visualise how the breakthrough technology can be implemented in their field. Also, if their application is assessed to be the most promising alternative, which is not part of the current framework, they can actually produce the desired application.

The ten steps are summarised in **Figure 5.1.1** below.

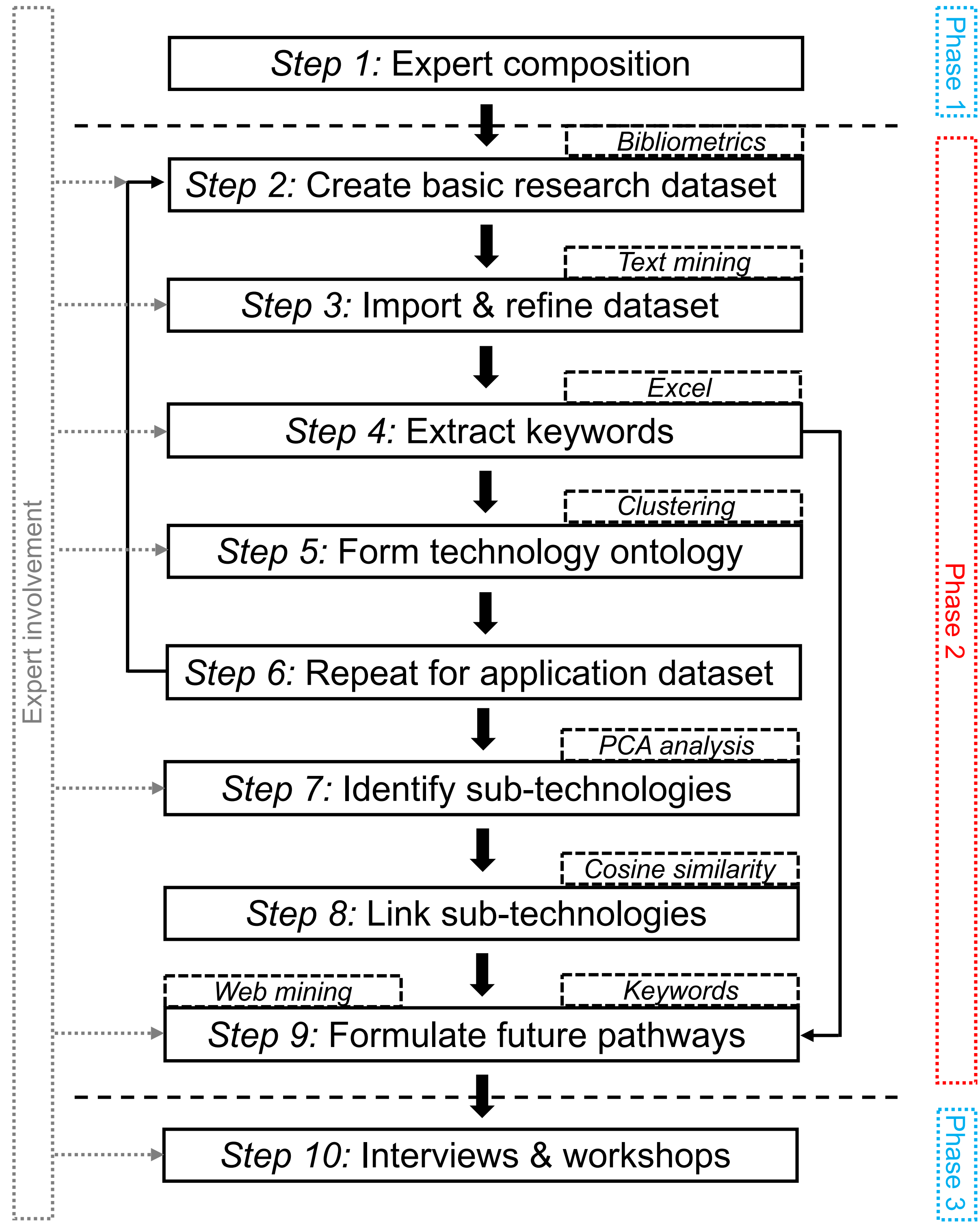

Figure 5.1.1. Overview of the ten-step framework designed for finding applications for a breakthrough technology. Where possible, the used heuristic is shown. Continuous expert involvement is also indicated. The blue phases make use of qualitative measures, whereas the red phase uses quantitative measures.

5.2 Partially applying the framework to quantum dots

In this subsection the aforementioned framework is partially applied to the case of quantum dots. The results are discussed below. The first step, gathering the groups of experts, was not carried out. However, the moments that experts should be involved are indicated.

5.2.1 Steps 2 and 3: creating and refining the technology profile and the application profile

First, the two databases in WoS were created, one related to the basic research conducted on QDs and one on the applications for QDs. The Boolean refinements of the search strings used for these two databases are summarised in **Table 5.2.1.1** below. Normally, the search queries should be reviewed and potentially adapted upon discussion with QD experts. The search on basic research yielded 14,576 documents. The search on applications resulted in 10,752 documents.

Table 5.2.1.1. Boolean refinement of the searches in WoS. The left-hand side represents the refinements for the basic research dataset. The right-hand side shows the refinements for the application dataset.

	Basic research		**Application**	
	Included	**Excluded**	**Included**	**Excluded**
Document type	Reviews and articles in peer-reviewed journals Book chapters	Other document types	Reviews and articles in peer-reviewed journals Book chapters	Other document types
Year of publication	2020 – 2023	Pre 2020	2020 – 2023	Pre 2020
Language of the article	English	Other languages	English	Other languages
Search terms present in title, abstract, author keywords, or keywords plus	"quantum dot*" OR "QD" AND NOT "quantum dot* application*" AND NOT "QD application*" AND NOT "overview" AND NOT "review" AND NOT "based on quantum dot*" AND NOT "based on QD"	Other search terms	"quantum dot* application*" OR "QD application*" AND NOT "overview" AND NOT "review"	Other search terms
Research area	Any research area	-	Any research area	-
Database	WoS	Other databases	WoS	Other databases

Because WoS only allowed for the extraction of a maximum of 1,000 files, the datasets of WoS were divided into sets of 1,000 records. The datasets were consequently merged, making use of Python. The merged datasets were imported into VantagePoint.

The databases generated in WoS were supplemented with patents from the Derwent Innovation Index (DII) and informal documents from ProQuest (former ABI/Inform). For both patent searches as well as both searches for informal documents roughly the same search terms and Boolean refinements were used as the ones for the searches in WoS. This resulted in 1,632 patents for the basic research dataset and 893 patents for the application dataset. The informal records consisted of newspapers, blogs, podcasts, and websites. The datasets were 929 records and one record large for the basic research and application search, respectively. The informal document concerning QD applications was discarded since it was only one record.

The patent records could only be exported in sets of 1,000. Therefore, the patent records were divided into sets of 1,000 records and the sets were merged, making use of Python. The informal documents could only be exported in sets of 500. Therefore, the informal records were divided into sets of 500 records and the sets were merged, making use of Python. The datasets were then imported into VantagePoint.
Only the datasets gathered from WoS contained author's keywords. Therefore, the patents and informal records were discarded. The title and abstract duplicates were removed from both the WoS technology and WoS application datasets. Next, the datasets were refined. As a first step, fuzzy matching of the author's keywords was done. The matching rulesets 'General' and 'BritishAmericanSpelling' were used. The Thesaurus tool was also applied to the author's keywords. The 'BritishEnglish' and 'Stopwords' Thesauri were selected. These refinements reduced the technology dataset and the application dataset to 14,541 and 10,739 records, respectively. The refinements should normally be discussed with the text mining expert(s).

5.2.2 Step 4: extracting the most used and most increasingly used keywords

The most frequently appearing author's keywords were gathered in VantagePoint for both datasets. The lists were exported to Excel to find the most frequent keywords for each year. The keyword "Quantum dot(s)" were excluded from each year. Keywords that were too close in meaning were also discarded. Normally, the results of this subsection are discussed with the technology experts. The ten most frequent keywords are given for each year for the technology dataset and the application dataset in **Table 5.2.2.1** and **Table 5.2.2.2**, respectively.

Table 5.2.2.1. The ten most frequent keywords per year of the technology dataset. The number of times a keyword appeared is shown between brackets.

	2020	2021	2022	2023
1	carbon dots (145)	photocatalysis (126)	carbon dots (160)	carbon dots (44)
2	senser (109)	carbon dots (119)	photocatalysis (127)	photocatalysis (30)
3	photocatalysis (104)	graphene quantum dots (107)	senser (121)	senser (26)
4	graphene quantum dots (96)	photoluminescence (93)	graphene quantum dots (107)	graphene quantum dots (20)
5	photoluminescence (93)	senser (89)	photoluminescence (88)	photoluminescence (17)
6	carbon quantum dots (76)	fluorescence (64)	fluorescence (73)	Density Functional Theory (DFT) (16)
7	fluorescence (58)	nanoparticles (56)	nanoparticles (56)	fluorescence (12)
8	nanoparticles (57)	sulphid (44)	colour (54)	colour (12)
9	solar cells (50)	nanocomposite (37)	sulphid (48)	optical properties (12)
10	colour (49)	colour (36)	perovskite (42)	sulphid (11)

Table 5.2.2.2. The ten most frequent keywords per year of the application dataset. The number of times a keyword appeared is shown between brackets.

	2020	2021	2022	2023
1	carbon dots (185)	carbon dots (201)	carbon dots (226)	carbon dots (78)

2	senser (177)	senser (153)	senser (191)	senser (44)
3	fluorescence (101)	graphene quantum dots (108)	graphene quantum dots (108)	colour (30)
4	graphene quantum dots (88)	photoluminescence (93)	colour (89)	photoluminescence (29)
5	photoluminescence (81)	colour (87)	fluorescence (87)	graphene quantum dots (28)
6	nanoparticles (65)	fluorescence (81)	photoluminescence (87)	fluorescence (26)
7	colour (61)	stability (51)	perovskite (68)	stability (20)
8	Light-Emitting Diodes (LEDs) (44)	perovskite (49)	stability (67)	perovskite (18)
9	photocatalysis (43)	nanoparticles (48)	nanoparticles (50)	bioimaging (16)
10	bioimaging (39)	bioimaging (45)	bioimaging (47)	photocatalysis (12)

The most frequently appearing keywords show that carbon quantum dots, QDs made of a carbon source, are investigated heavily in the recent years. This is not surprising, as alternative, more environmentally benign QDs compared to traditional CdSe are being investigated heavily. This is backed up by the fact that graphene quantum dots also score high in the tables, which are a type of carbon QDs (namely QDs made of graphene, a type of carbon). Next to this, sensers that incorporate quantum dots are apparently also investigated profoundly. The field of photocatalysis is more important in the basic research on QDs than in the applications surrounding QDs. Quite interestingly, perovskites show up in the application dataset quite often, although this is a relatively new class of nanocrystals (and would therefore be more logical in the basic research dataset). Also, still many researchers seemingly focus on synthesis of QDs, as many terms related to synthesis and performance can be distinguished (e.g., fluorescence, photoluminescence, and stability). DFT calculations, carrying out computations on large clusters of atoms via a supercomputer, is gaining attention very recently, too. Finally, important application fields that make use of QDs appears to be optics (LEDs) and bioimaging.

Next, the lists of most frequent keywords that were collected earlier were exported to Excel and the increase in use of each keyword, compared to the year before, was calculated. The ten most increasingly used keywords for the years n-2 until n are shown for the technology dataset and the application dataset in **Table 5.2.2.3** and **Table 5.2.2.4**, respectively.

Table 5.2.2.3. The ten most increasingly used keywords per year of the technology dataset. The percentage increase compared to the year before is given in brackets.

	2021	2022	2023
1	carbonise (600)	biosensing (800)	photonics (200)
2	ligands (600)	behaviour (600)	tetracycline hydrochloride (200)
3	double quantum dots (500)	charge balance (600)	liquid crystals (200)
4	silver (500)	Nikiforov-Uvarov method (600)	machine learning (200)
5	clinical trial (500)	p-n heterojunction (600)	coupling (200)
6	additives (500)	third-harmonic generation (600)	photoelectrocatalysis (200)
7	metal ion detection (500)	ratiometric fluorescence (500)	pyrolysis (200)
8	quantum efficiency (400)	water oxidation (500)	synergistic effect (100)

9	mechanical properties (400)	metal oxide (500)	Alzheimer disease (100)
10	silicon photonics (400)	Tetrel bond (500)	anti-counterfeiting (100)

Table 5.2.2.4. The ten most increasingly used keywords per year of the application dataset. The percentage increase compared to the year before is given in brackets.

	2021	2022	2023
1	photonics (900)	oxidative stress (600)	miRNA (300)
2	$CsPbBr_3$ nanocrystals (800)	high stability (600)	dielectric properties (200)
3	indium phosphide (700)	semiconductor lasers (600)	CuS (200)
4	laser (600)	logic gates (600)	living cells (200)
5	organophosphorus pesticides (500)	aggregation-induced emission (550)	polydopamine (150)
6	charge transport (400)	carbon quantum dot (500)	curcumin (150)
7	coating (400)	mercury ion (500)	interface (100)
8	DFT calculations (400)	rhodamine B (500)	QDSSC (100)
9	high PLQY (400)	methyl orange (500)	resistive switching (100)
10	time-resolved photoluminescence (400)	gaussian white noise (500)	bandgap (100)

There does not appear to be a pattern in the most increasingly used keywords. The columns are highly heterogenous compared to the lists of most frequent keywords. Where one term is highly upcoming in one year, it can be rather irrelevant in the next, and vice versa. This hints that there is still a lot of technological uncertainty surrounding QDs. If there was more technological certainty, the lists would have been more coherent. It is apparently not yet clear what the technology can do, how it can be incorporated into applications, and whom the technology might be useful for. This, in combination with the fact that there have been some applications that have been introduced to the market, confirms the earlier statement that QDs are in the adaptation phase. This observation is not illogical, as section **2.5.1 Three phases in the development and diffusion of applications** narrated that the length of the phases of the pattern of development and diffusion of breakthrough technologies can vary heavily. It is therefore not unthinkable that the adaptation phase for QDs lasts significantly longer than the average ten years. This observation could mean that further execution of the framework on QDs will result in some issues, since section **4.2 Factors influencing the process of finding applications for a breakthrough technology** indicated that the framework is only applicable to breakthrough technologies that are still in the innovation phase.
The increasingly used keywords of 2021 and 2022 will later on be put in the TRMs, belonging to a certain, yet to be determined, main field, to predict the short-term future pathways of 2024 and 2025, respectively.

5.2.3 Steps 5 and 6: forming the ontologies

The co-occurrence matrices of the author's keywords were generated, next. The records that were only occurring once or twice were removed. This reduced the technology matrix from a symmetric matrix of 21,843 rows and columns to a symmetric matrix of 2,733 rows and columns, and the application matrix from a symmetric matrix of 15,893 rows and columns to a symmetric matrix of 2,031 rows and columns. The matrices were exported to Excel. Following up on this, the keywords that made no sense were removed, reducing the technology matrix to a symmetric one of 2,715 rows and columns, and the application matrix to a symmetric matrix of 2,021 rows and columns. This refinement of the matrices is normally discussed with the text mining experts and the technology experts. The empty fields were replaced with zeros since some of the computations carried out to the co-occurrence matrices require the input of the rows and columns to be numeric values.

The matrices were saved and imported into R programming software. The code that yields the dendrogram that forms the basis for the technology ontology is shown in **Appendix 4: coding for R**. This code should normally be discussed with the text mining experts.

The distance matrix, which is used as input for the dendrogram, that is generated by this code should be a matrix with the same dimensions as the co-occurrence matrix, yield zeros on the main diagonal (since two identical keywords are totally similar), yield non-zero values in the remaining fields, and should be symmetrical around the main diagonal (just like the co-occurrence matrix). Since it is hard to check whether the distance matrix meets these requirements with co-occurrence matrices of large dimensions, the entire code was also run on a self-created co-occurrence matrix of ten rows and ten columns. For all steps in the code, it was verified that the code indeed produces the desired outcome. Eventually, the code generates a matrix that has the same dimensions as the co-occurrence matrix, contains zeros on the principal diagonal, produces non-zero values in the remaining fields, and is symmetrical around the main diagonal. Therefore, the code can be considered as correct and the resulting dendrograms are thus trustworthy. The verification of the code designed to generate the distance matrices is shown in **Figure A.4.1** in **Appendix 4: coding for R**.

The resulting technology dendrogram and application dendrogram are shown in **Figure 5.2.3.1** and **Figure 5.2.3.2**, respectively.

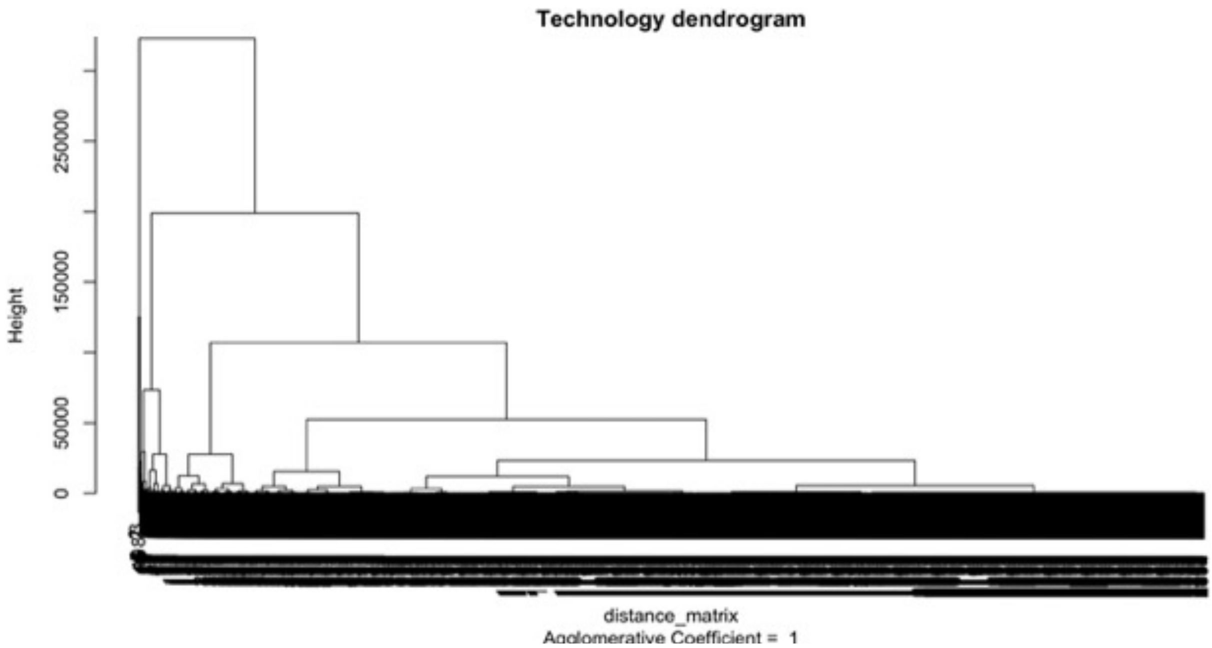

Figure 5.2.3.1. The technology dendrogram.

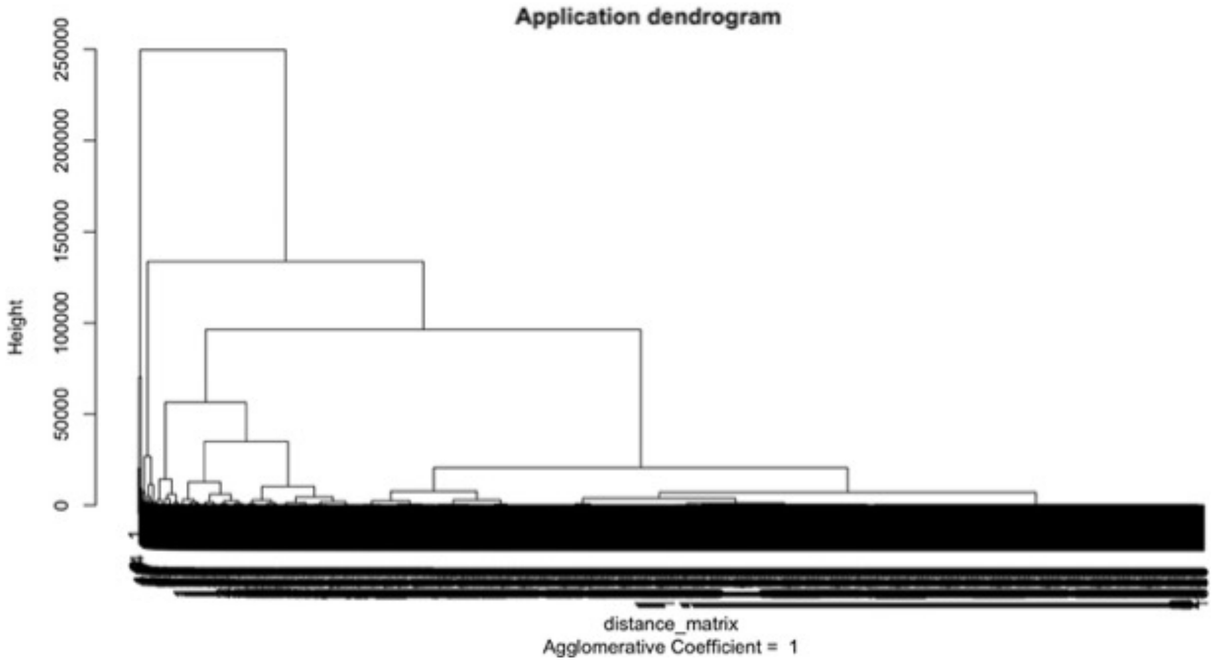

Figure 5.2.3.2. The application dendrogram.

The agglomerative coefficient that is shown at the bottom of the two dendrograms shows how well the structure of the distance matrix is maintained in the dendrogram. In other words, it indicates if clustering the keywords into a dendrogram is appropriate. The coefficient is represented by a value between zero and one, where a value of one means that the keywords can be clustered in a dendrogram, perfectly, and where a value of zero indicates that the clustering into a dendrogram is not appropriate at all. The previous two figures show that both sets of keywords can be clustered into a dendrogram perfectly. The dendrograms are thus a suited and reliable input for the creation of the ontologies.

These dendrograms are, as mentioned, not the ontologies that are needed. To obtain the ontologies, the dendrograms must be analysed. The dendrograms as produced by the provided code are complex and detailed, and this level of complexity must be reduced. The number of clusters must be cut down to a manageable quantity. The y-axes of the dendrograms, titled “height”, can be used for this purpose. The y-axis namely represent a degree of dissimilarity between the branches of a dendrogram. If branches are highly dissimilar, the height difference between the branches will be large. If branches are more alike, the height difference between the branches will be small. Some of the branches of the dendrograms need to be combined, so that only clusters with relatively large height differences remain (and thus combining branches that are highly similar), which represent large dissimilarities. An example of the technology dendrogram that is clustered into eighteen groups is shown in **Figure 5.2.3.3** on the next page. The coding that can be used to obtain these clusters is described in **Appendix 4: coding for R**.

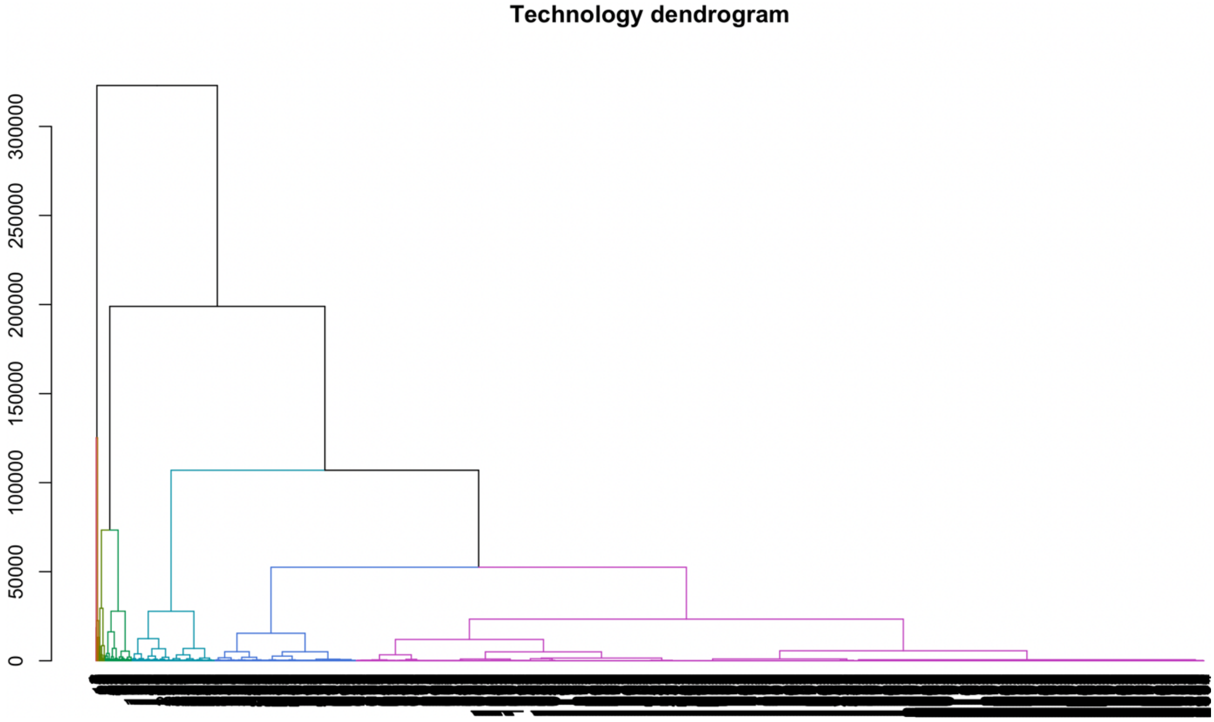

Figure 5.2.3.3. The technology dendrogram clustered into eighteen groups. Each colour represents a cluster.

After the complexity of the dendrograms is reduced, the terms that are included in each cluster (the terms that are categorised under the same colour) must be analysed to attribute an overarching name to each cluster. Since some clusters contain many keywords, which makes it hard to find one encompassing term that describes that cluster, only clusters with a manageable number of keywords in it are named. By doing this, however, many keywords are discarded, and possibly relevant clusters are disposed of. As remarked in section **5.2.2 Step 4: extracting the most used and most increasingly used keywords**, this is a noteworthy issue that is probably the resultant of the fact that QDs are already in the adaptation phase, rather than still being in the innovation phase. If QDs were more in their infancy, the number of keywords would probably be drastically fewer, resulting in more manageable dendrograms. For these more manageable dendrograms, the clustering of similar keywords would most likely result in clusters of smaller sizes, making it redundant to dispose clusters that contain many terms (because only clusters with a manageable number of keywords would be present).
The names of the clusters of the dendrograms form the first layer of the ontologies. These terms will be used as main fields in the vertical axes of the TRMs. However, this step, and the steps that follow, were not carried out in this thesis project.

To complete the execution of the ten-step framework on QDs, names have to be given to the clusters of keywords, first. Then, the ontologies are formed, concluding steps 5 and 6. The terms of the ontologies correspond with the vertical delineation of the TRMs. They represent the main fields of the TRMs. Next, steps 7 – 10 need to be carried out. In step 7, sub-technologies belonging to the main fields are discovered by dividing the datasets into years in VantagePoint and attributing each sub-technology to a certain main field. During step 8, links between the sub-technologies of the technology TRM and sub-technologies of the application TRM are discovered through programming a cosine similarity. In step 9, the short- and medium-term future sub-technologies are placed in the TRM. The short-term future sub-technologies are retrieved from the most increasingly used keywords (tables **Table 5.2.2.3** and **Table 5.2.2.4**) and the medium-term future sub-technologies are gathered through web content mining. After this step, the TRMs are finalised. Finally, during step 10, the last group of experts are adjusted based on the future sub-technologies. These experts are then interviewed, first, and together with them possible future applications for QDs are formulated in two workshops. The TRMs, and the process of its construction, form the starting point of these interviews and workshops.

6. Discussion and future research

This section discusses the current thesis report and gives directions for future research. It starts with answering the research questions, as drafted in subsection **1.3 Research objective and research questions**, in subsection **6.1 Answering the research questions**. Then, the scientific contribution and the managerial contribution is indicated in subsection **6.2 Scientific and managerial contribution**. Following up on this, the steps taken to construct the ten-step framework and its partial application to the case of QDs is discussed in subsections **6.3 Steps taken to construct the ten-step framework** and **6.4 Partially executing the ten-step framework on quantum dots**, respectively. Finally, in subsection **6.5 Generalisability of the ten-step framework**, the generalisability of the ten-step framework is discussed.

6.1 Answering the research questions

In the beginning of this thesis, two main research questions were drafted. The first question was made up of five sub questions. The questions are answered below.

(1) How can one systematically find applications for breakthrough technologies?

(1.1) How can a (breakthrough) technology be defined?

Answer: *A technology can be defined as the tools or knowledge that can be used to create and produce goods and services, solve problems, and facilitate (new) products. Dimension-wise, a technology is the smallest unit of analysis within a domain or field.*
A breakthrough technology is a technology where the discontinuity of the radical technological change is so profound that it can potentially lead to a major enhancement in the price-performance ratio or even result in new product classes. Both the technological dimension and usage dimension are unstable when a breakthrough technology surfaces.

(1.2) How can an application be defined?

Answer: *An application can be defined as an innovation (a product, service, or process made up of several subsystems that incorporates a technological principle to fulfil a certain functionality) serving a particular customer group, with certain preferences, in a particular usage context.*

(1.3) What methodologies for creating a list of applications for a breakthrough technology are existent?

Answer: *Five frameworks were found that can be useful in formulating a list of possible future applications for a breakthrough technology. None of these frameworks, however, create a list of applications for a breakthrough technology as I define the term application.*

(1.4) What are factors influencing the process of formulating applications for an emerging technology?

Answer: *It must not be obvious what the breakthrough technology can do, how it can be used, or whom it could serve. Next to this, these parameters must also be unsure. The breakthrough technology must still be in the innovation phase.*
The process of formulating a list of possible future applications for a breakthrough technology should combine qualitative methods and quantitative approaches in a balanced way. Additionally, experts should be involved

continuously, and it should be clear who the experts are. Then, it is important that a look at the future is taken and that concrete applications for the breakthrough technology are formed.

(1.5) How can a set of possible future applications for a breakthrough technology be formulated by taking the discovered methodologies and factors into account?

Answer: *Possible future applications for a breakthrough technology can be composed by executing the ten-step framework suggested in this thesis.*

(2) Which possible future applications can be found for quantum dots?

Answer: *This final question could not be answered as the ten-step framework, applied to QDs, was not executed until completion.*

6.2 Scientific and managerial contribution

By answering the above research questions, I contributed to the scientific and managerial world in several ways. Firstly, I pointed out that the constructs of (breakthrough) technologies and applications are multifaceted. The concepts are abstract and used in a plethora of ways. I gave more clarity on their definition and dimensions.
Next to this, I summarised the relevant frameworks that are useful for finding applications for a breakthrough technology. As far as I know, no one has done this before. Then, I made suggestions for factors that are of importance in the process of formulating possible future applications for a breakthrough technology, since these factors are not well-established in existent literature. Based on these success factors, I compared the five frameworks to each other, which is also something that has not been done before. I concluded that none of the frameworks result in a list of possible future applications for a breakthrough technology (as I define an application) and I thus proposed a more suited framework for this purpose. The steps in this framework are explained in greater detail when compared to explanations provided in other frameworks, increasing the reproducibility of the framework. I partially executed this framework to the case of quantum dots to initiate the process of formulating possible future applications for this emerging technology. I discovered that executing the proposed framework on a breakthrough technology in the adaptation phase results in problems, and that the framework is better suited for breakthrough technologies that are still in the innovation phase.

Taking the above points together, I introduced a new, more structured way of thinking about and approaching the NPD process, which is a process that is exceptionally uncertain in nature. I think that initiating a differing line of thought about this process, and providing tangible handles to better structure this habitually chaotic process is my biggest contribution, scientifically as well as managerially, as elaborated upon above.

6.3 Steps taken to construct the ten-step framework

For starters, the terms (breakthrough) technology and application were defined. These definitions are crucial since they form the theoretical basis of the current thesis. The definitions are namely determining in the consecutive steps within this project, for example when it was recognised that a framework for finding applications for a breakthrough technology was non-existent. If the definitions were formulated differently, it could be that such frameworks do exist, and the symbiosis suggested in this thesis would not have been necessary. Also if, for example, the term application was defined in a simpler way, e.g., as an innovation (since application and innovation are used interchangeably in literature), the final step of the ten-step framework would be much simpler. The experts would then only have to think of what the

technology can do and how it can be incorporated in a product, service, or process with subsystems.
Next to this, the definition of, for example, the term application as provided in the current work has its implications on the successive steps in the NPD process. If, by means of illustration, the usage context of the social entities is not taken into account, by leaving it out of the definition, this has serious consequences. If we think back to the example of the camera, the groups of experts that are formulating the set of possible future applications for the breakthrough technology of a light-sensitive cell then would not have made such a clear distinction between several applications. If the only parameters they had to look in to where the social units and their preferences, the experts would have only made the distinctions between adults and adolescents that want to capture moments. The whole discussions about battery life, wireless connection, and portability would have been redundant. This would have led to a shorter list of applications and the applications would have been defined in less detail. Since the set of applications is smaller and defined in lesser detail, the selection step that follows becomes simpler. However, since some details about the applications are missing, barriers might be faced that hinder the further development of the most promising application. These hurdles might have been seen if the definition of an application was formulated as in the current work.

In other words, the definitions are subjective. The terms were defined based on how I look at the concepts, and the 'problems' I discovered that these constructs are surrounded by. The current definitions are profoundly based on literature, discussions with my supervisor, and tangible examples that I could think of. It appeared to be hard to find common ground in terms that are used in a wide variety of contexts and that are used in differing dimensions. Therefore, future research must re-evaluate the definitions provided in this thesis and possibly adapt them as seems appropriate.

Next, a literature review was carried out to discern existent methodologies for finding applications for a breakthrough technology. The way the literature review was designed leads to some limitations.
Firstly, only reviews, articles, and book chapters were reviewed. However, there could be other types of records that describe how applications for a breakthrough technology can be found, for instance conference papers. It is not expected that much relevant literature is missed by only including reviews, articles, and book chapters, since these types of records made up the top three of document types with the most records in it, but future researchers should be aware of the fact that potentially relevant literature is excluded by only looking at reviews, articles, and book chapters.
Additionally, the search terms as provided narrow down the scope of the literature review. For example, the Fuzzy-Front-End is not included into the search. Broadening the search terms could increase the number of relevant frameworks found.
Scopus was used as the only database in the literature review. There could be other databases, e.g., WoS or Google Scholar, that contain relevant records that are not published on Scopus. Performing the same search to find methods for finding applications for a breakthrough technology as the one performed in Scopus namely resulted in 588 records in WoS (compared to 143 in Scopus). Enlarging the number of databases could yield supplementary frameworks that are overlooked by only relying on Scopus.
Next to this, only records that were cited at least twenty times were included in the search. More recent literature, that has not been discovered by many others and is thus cited infrequently, for example, is not included through this refinement. Including records with fewer citations could therefore lead to other relevant frameworks.
Finally, some aspects of the literature review are not anticipated to limit the search.
Records published before 1990 were excluded, but this is not expected to limit the current work. The way of thinking about the NPD process as set forth in this thesis appears to be rather new (since so little could be found about formulating a set of alternative applications before diving into the NPD process), and the five relevant frameworks that were found were all

articulated in the past fifteen years. Therefore, looking into literature that has been published before 1990 is not expected to yield additional frameworks.
The subject area of business, management, and accounting is most likely also not hampering the literature review. Management is included, and the problem at hand mostly concerns how one *manages* the NPD process. Widening the number of subject areas is therefore not expected to result in supplementary frameworks.
The fact that only records written in English were included probably also does not hinder the search for frameworks for finding applications for breakthrough technologies, as most relevant literature is either written in English or is translated into English.
Keeping the aforementioned critiques in mind, future research could redo the literature review to include frameworks that were left out by the current literature review.

The fact that only a literature review has been carried out to figure out how applications for a breakthrough technology can be found is itself a limitation to the current work as well. For example, interviews with innovative companies and/or academia could be included to gain more insights from practice. It could be that successful, highly-innovative companies rely on the tacit knowledge of employees, rather than them writing down and publishing what they do. Interviews to acquire this kind of tacit knowledge were not conducted in the current work and future research could try to include the views of practitioners to find out how they formulate applications for a breakthrough technology.

The two aforementioned points about the literature review that was set up to find ways of formulating applications for a breakthrough technology also apply to the literature review that was established to discover factors that are of importance in this process. Knowing the success factors in the process of formulating applications for a breakthrough technology helps understanding the process. Being aware of what matters in the process can aid in designing a methodology. Since the success factors were not discovered in the current research through a literature review, but were formulated based on my judgement, future research must evaluate whether the success factors make sense and if they should be adapted and/or expanded. If the set of factors is altered, the ten-step approach suggested in this thesis can be adjusted based on the updated factors.

Within the ten-step framework, I argued that quantitative methodologies and qualitative approaches should be combined in a balanced way to mitigate each other's shortcomings. However, no metric was provided to assess whether the qualitative methods and quantitative procedures are indeed balanced. Future research should somehow find a way to indicate if qualitative approaches and quantitative methodologies are used in a balanced way, and measure if this is indeed the case for the framework proposed in the current work. The ten-step framework can then be adapted as is appropriate.

The ten-step framework that is suggested in this thesis is based on a (basic) comparison of the five frameworks. The judgement of the shortcomings of framework 4 and how the other frameworks can aid in circumventing these inadequacies are subjective. Other combinations of the frameworks might be thought of that are also effective for formulating a set of possible future applications for a breakthrough technology.

The resultant of the ten-step framework is a list of possible future applications for a breakthrough technology. However, the framework does not give any guidelines to judge whether the list that is discovered through executing the framework, is complete. If the list of applications is incomplete, and the most-promising application is selected from this inadequate list, potentially more appropriate applications are overlooked. The NPD process would then fall back to the chaotic trajectory, as it is realised that the application that is being developed further is not the most promising one. This would lead to the withdrawal of that application, and the reintroduction of a different, more fitting application. Framed differently, executing the framework makes no sense if the expert cannot be certain that the eventual list of applications is all-encompassing. This observation is of uttermost importance and managers should be very well aware of it. To mitigate this shortcoming, future researchers must supplement the ten-step framework with metrics to assess whether the eventual list of possible future applications for the breakthrough technology, is complete.

The framework proposed in the current thesis makes it possible to generate a set of possible future applications for a breakthrough technology. However, the framework does not provide a methodology for evaluating these future scenarios. Future research must look into possible ways of evaluating the set of alternatives, so that the most promising alternative can be chosen for further development. When determining which application is the most promising, both the long-term and the short-term should be considered. It could be that some applications are more desirable in the long-term, but that current barriers surrounding these applications make it that other applications (which are currently not hampered by diffusion barriers but are less promising in the long-term) are more suited in the short-term. In this case, it could be that some less fitting applications should be introduced to customers first, before moving on to the applications that are most fruitful in the long-term. Directions for the judgement of a set of alternative applications that can be looked in to are the judgement of the readiness of applications based on seven core actors and seven influencing factors as described by Ortt and Kamp (2022), or by looking at a combination of readiness levels of the applications as explained by Vik et al. (2021).

Finally, by executing the ten-step framework, a set of possible applications for a breakthrough technology will be the outcome. After evaluating the alternatives and choosing the most potent one for further development, the framework assumes that the rest of the NPD process runs smoothly from here, since time and resources will be attributed to the superior application. In reality, the process will probably stay erratic, and the introduction of applications will most likely still be surrounded by multiple withdrawal and reintroduction cycles. The NPD process is surrounded by so much uncertainty that it will almost certainly never be a linear, efficient process. This is something that managers should be aware of.

6.4 Partially executing the ten-step framework on quantum dots

First of all, it was decided to partially evaluate the ten-step framework by partially executing it on the case of QDs. However, the framework could also be evaluated by applying it to an older breakthrough technology that is at the moment in the market stabilisation phase. The framework could be applied to this breakthrough technology by selecting a time range when the breakthrough technology was still in the innovation phase. The prediction of the list of possible applications that are generated for this breakthrough technology can then be compared to the applications that were developed in actuality. If the list of possible applications coheres with the list of actual applications, the framework could be judged to be effective in reaching its intended goal. If this is not the case, the framework could be adjusted based on the findings. Therefore, future researchers must execute the ten-step framework on an established breakthrough technology currently in the market stabilisation phase (but only incorporating the records at the time the breakthrough technology was still in the innovation phase). The future researchers can then reshape the ten-step framework as they seem fit.

Alternatively to this, QDs were chosen as the exemplary breakthrough technology to partially apply the ten-step framework to in the current work. Since newness is not a determining parameter in my definition of a breakthrough technology, QDs can indeed be classified as a breakthrough technology in the current work. However, novelty might be something that must be looked at when recognising emerging technologies. Based on the dendrograms being too complex for QDs (which is a breakthrough technology in the adaptation phase), it was concluded that the ten-step framework is best applicable to breakthrough technologies still in the innovation phase. This hypothesis is supported by the fact that cloud computing, the breakthrough technology that was analysed in framework 4, which is the framework that forms

the basis of the present ten-step framework, is more in its infancy than QDs. The technology was discovered only in 2008. The basic research dataset that the researchers worked with there consisted of only 3,194 records, compared to 14,541 records for QDs, despite the time range for CC being six years and that of QDs being only 3.5 years. Therefore, the dendrograms of CC will most likely be of significant lesser complexity. If the dendrograms of CC are substantially simpler than the ones for QDs, since they contain fewer keywords, clustering terms and giving names to these clusters will be easier and more appropriate. This hints that CC is more in its infancy than QDs, and that the claim that framework 4 can "…be applied to any kind of emerging technology" (Bildosola et al., 2017, p. 28) might be too generic.
Next to the observation on the dendrograms, it was concluded that it makes more sense to formulate a set of possible future applications for a breakthrough technology in the innovation phase, since then the possible pathways of the technology are most uncertain. When some applications of the breakthrough technology have already been introduced to the market, placing the technology in the adaptation phase, directions for possible applications already become apparent, and in this scenario it is thus less logical to formulate a set of alternative applications.
In this light, QDs already have matured quite a bit since their discovery in the 1980s. It was namely concluded that QDs are already in the adaptation phase, rather than still in the innovation phase. Framed differently, there might be alternative breakthrough technologies within the field of nanotechnology (that are still in the innovation phase) that are more suited for the current analysis.

In the execution of the ten-step framework on QDs, the sets of experts were not gathered. The experts are crucial to the framework since their continuous involvement forms most of the qualitative part of the framework (and thus counterbalances the quantitative part) and steers the process as it develops. The experts introduce expertise of fields that the researcher carrying out the framework has limited know-how about, for instance most of the text mining procedures. Therefore, it is vital that future research starts off the framework with the right sets of experts and involves them actively.
Next to this, the composition of the set of experts, especially the insiders and outsiders to the technology, is highly dependent on the characteristics of the technology itself and on the outcome of the future sub-technologies of the TRMs.
For example, QDs are surrounded by pressing toxicity problems. This is probably also why carbon dots are such an emerging direction in the QD world, as they potentially eliminate these toxicity concerns. Keeping this in mind, environmentalist and health experts can be imagined to be experts that are of uttermost importance in the process of formulating possible applications for QDs. For CC, these experts can be envisioned to be superfluous.
Also, the future sub-technologies of the TRMs, which indicate in which fields a breakthrough technology can be applied, give directions for which insiders and outsiders to the emerging technology must be involved. Since these sub-technologies only become apparent as the execution of the framework progresses, composing this set of experts is something that must be steered continuously as well.
These two observations are something that managers should be aware of.
Lastly, it should be noted that there could be multiple viewpoints on how to involve the experts. Whereas many existent frameworks work with *active involvement* of experts in some sort of group session, I suggest that part of the experts should be approached through *interactive partnerships*. Rather than letting each expert have their say and leave it with that, the experts should be seen as the basis for the generation of the set of possible applications for the breakthrough technology. Especially the experts in the sub-technologies that appeared to be relevant from the TRMs should be leading. They have much expertise in the field they are operating in, and can thus best imagine how the technology could possibly be used in their area. Also, they can potentially develop a certain application that incorporates the breakthrough technology, if it is assessed as the most promising alternative, and should therefore be seen as the backbone of the workshop sessions.

The generation of the technology and the application profile should be discussed next. As stated in the framework, multiple types of records should be included to retrieve all-encompassing datasets on the breakthrough technology. However, it appeared to be practically challenging to include the patents and informal records since they both lacked author's keywords. This is problematic, because they can thus not be included in the datasets, which leads to a narrower view of the emerging technology. In future research it can be seen if other fields that might summarise what a record is about, for instance regular keywords or keywords plus, can be combined with the author's keywords of the scientific literature. In this way, the other types of records can be included. Future researchers must be aware that this could increase the datasets significantly, though.
Next to this, only 69% and 71% of the records that were included in the QD analysis contained author's keywords for the technology profile and application profile, respectively. This means that about one third of the retrieved records were not included in the current analysis. Therefore, keywords could be missing and the links between the keywords, given by the co-occurrence matrices, might be skewed. To remove this bias, future research must preferably work with datasets in which all records contain (author's) keywords.
Obtaining the most frequent keywords was not accompanied by any trouble and the lists of keywords were rather coherent. However, when retrieving the most increasingly used keywords, the formula in Excel used does not work if one divides by a non-numeric value (or by zero). Therefore, if a term did not appear in, let us say, 2020, but did appear in 2021, this increase cannot be calculated, and the term is excluded from the list despite it potentially being relevant. Only increases are incorporated if the keyword was already present in the year before. To circumvent this issue, future researchers could attribute a non-zero value to keywords that are not occurring in a certain year (e.g., 0.01). In this way, one never divides by zero and all keywords can be incorporated, even if a keyword did not appear in the year before the year of calculation.
Next to this, the lists of most increasingly used keywords are found to be heterogenous. There does not really seem to be a pattern in what terms are (becoming) important. Reason for this could be the previously mentioned point, in combination with the fact that there are often many terms that score the same (e.g., the score of 200% increase in the 2023 technology set: could be place 1 or place 7). To see if there is some coherence in the lists, more keywords must be analysed than just the top ten. Finally, it could also be the case that there is no dominance in what direction QDs are moving, because the technology is still surrounded by a lot of (technological) uncertainty, even approximately 30 years after their discovery. This is not an odd scenario, as the phases of the pattern of development and diffusion can vary in length greatly. The adaptation phase sometimes takes multiple decades as described in section **2.5.1 Three phases in the development and diffusion of applications**. The heterogeneity of the lists of increasingly used keywords makes it hard to accurately predict the short-term future of the breakthrough technology. To verify whether this heterogeneity is present only for QDs, future research must execute the ten-step framework to other breakthrough technologies, that are still in the innovation phase, and see if the increasingly used keywords are more coherent there (and it is thus more accurate to use them as predictors of the short-term future of that breakthrough technology).

Penultimately, the constructed dendrograms look very complicated. A dendrograms is a tree diagram that visualises the similarity between keywords, in this case based on the distance matrix gathered in R (which is in turn based on the co-occurrence matrix retrieved from VantagePoint). To structure the dendrograms, it is suggested to cluster keywords with little difference in height on the y-axis (and are thus rather similar) of the dendrogram together. The technology dendrogram could, for instance, be reduced to eighteen clusters. Some of the clusters contain a manageable number of keywords, but the biggest cluster, by means of example, contains 1,105 keywords. Finding a name that describes all the terms in it is almost undoable for clusters of this size. Therefore, it was suggested that only clusters with a manageable number of keywords in it were analysed. By doing this, however, most of the keywords are discarded and relevant clusters could be disposed of.

It is expected that the dendrograms for breakthrough technologies that are more in their infancy than QDs will be less complicated since they potentially contain significantly fewer keywords, as elaborated upon earlier. The ten-step framework is thus probably more suited for newer breakthrough technologies (in the field of nanotechnology) than QDs. Future research must therefore execute the ten-step framework to a newer technology (in the field of nanotechnology) than QDs (a breakthrough technology still in the innovation phase) to see whether the datasets contain less records and thus yield less complex dendrograms, which can be clustered more effectively.

Finally, the steps that follow after construction of the dendrograms were not carried out in the present thesis. Future research must finish the framework for the case of QDs to find its possible future applications.

6.5 Generalisability of the ten-step framework

Table 4.2.2 summarised the characteristics that a breakthrough technology must adhere to for the ten-step framework proposed in this thesis to be suited to formulate the technology's possible future applications. These characteristics included non-obviousness and uncertainty of what the technology can do, how it can be implemented into applications, and its possible future users. In addition to this, the breakthrough technology must still be in the innovation phase.

Therefore, although it is hard to make the statement that the current framework is not useable at all for breakthrough technologies of the same level of novelty as QDs stick, since the framework was not fully executed, it is expected that the current framework is better suited for breakthrough technologies that are more in their infancy than QDs. The reasoning behind this statement is given earlier in this discussion section. As stated in section **3.2 Verification of the framework by applying it to a case**, QDs are already in the adaptation phase. It is expected that the current framework is better suited for breakthrough technologies that are still in the innovation phase, when it is highly uncertain in which direction the technology can develop and no applications that rely on that breakthrough technology are introduced to the market, yet. Therefore, future research must carry out the current framework to multiple breakthrough technologies that are still in the innovation phase.

Next to this notion of newness, the current framework is expected to be applicable to any breakthrough technology in any field as long as it is non-obvious and unsure what the technology can do, how it can be implemented into applications, and whom it might serve. Reason for this is that the text mining, which makes up a major part of the framework, is based on three types of records that are available for almost any breakthrough technology, even when the technology is still in the innovation phase. To test this hypothesis, future research must carry out the framework on multiple breakthrough technologies, still in the innovation phase, within differing fields.

7. Conclusion

In this thesis project, a ten-step framework is composed that is suited to find possible future applications for a breakthrough technology.

The reshaping of the chaotic NPD process into a more structured process, by introducing a pre-FFE phase where the ten-step framework can be executed, is displayed again in **Figure 7.1** below.

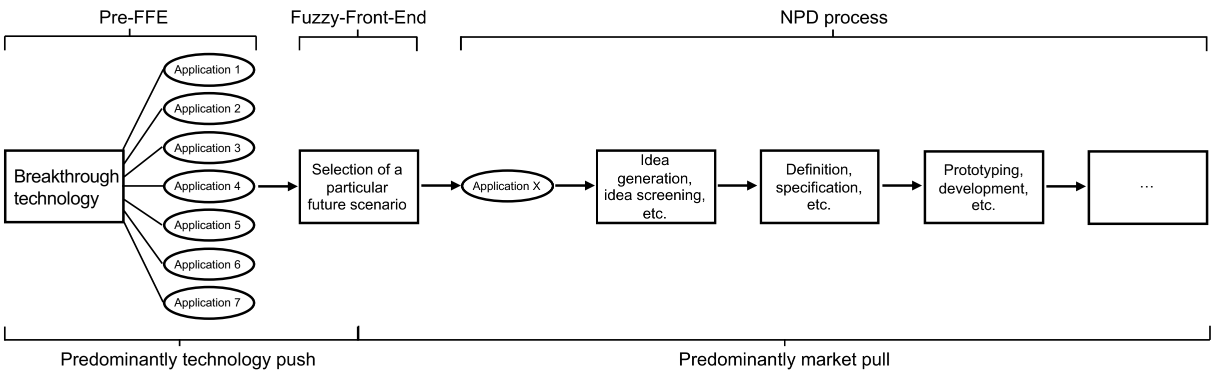

Figure 7.1. The total NPD process as I envision it. The problem addressed in this thesis is located in the pre-FFE phase, being the very start of the NPD process when the breakthrough technology has just surfaced.

But what are the implications of introducing the pre-FFE phase, and the accompanied ten-step framework, to the total NPD process?
To answer this question, the pattern of development and diffusion of breakthrough communication technologies is shown again in **Figure 7.2** below.

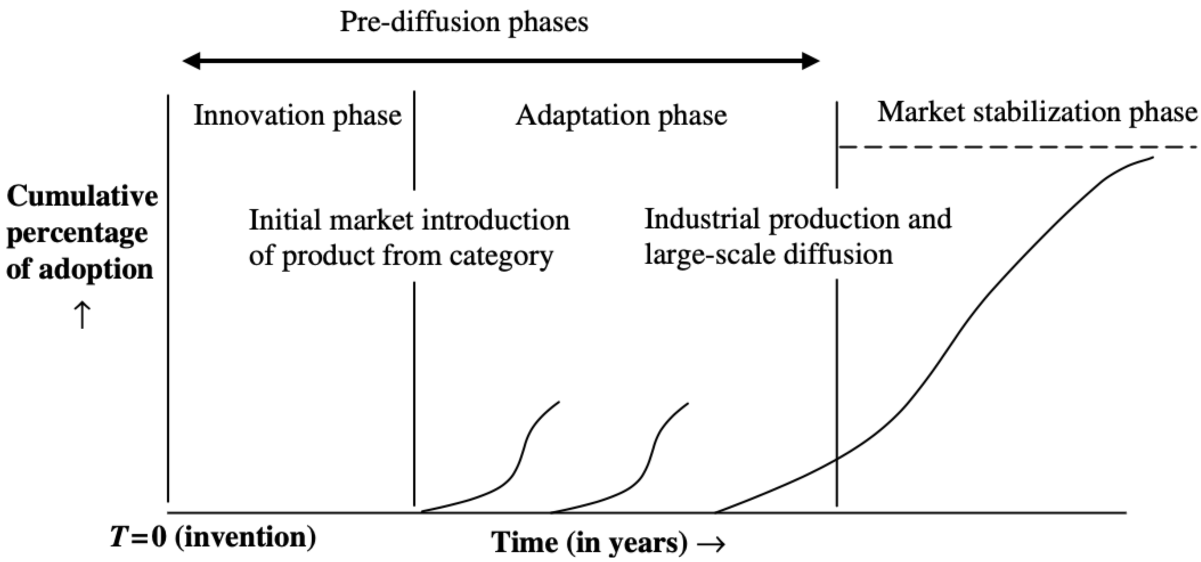

Figure 7.2. A schematic overview of the pattern of development and diffusion of breakthrough communication technologies. Reprinted from Ortt (2010).

The pattern reveals that once an application that relies on a certain breakthrough technology is introduced to the market for the first time (ending the innovation phase), it is withdrawn and reintroduced to the market during the adaptation phase. The multiple cycles of introduction, withdrawal, and reintroduction within the adaptation phase are caused by barriers that surround the applications that are being introduced. These barriers are only discovered as the adaptation phase proceeds. Eventually, the most promising application will end the adaptation

phase. The adaptation phase is then left behind, entering the market stabilisation phase, and the best-suited application is diffused on a large scale.
The outcome of the ten-step framework proposed in the current work is a list of potential future applications for a breakthrough technology. By selecting and further developing the most potent application from this list, the adaptation phase can be overleaped completely. Since the most promising application is being developed and consequently introduced from the start, there is no need to withdraw and reintroduce the application. The best-suited application that would normally eventually end the adaptation phase, is being developed and introduced from the beginning. This application can thus immediately enter the market stabilisation phase, saving companies a tremendous amount of scarce resources that would otherwise have been used up during the multiple cycles of introduction, withdrawal, and reintroduction.
This is obviously a bold statement. Skipping the adaptation phase entirely is of course the ideal scenario. In reality, it is most likely that the total NPD process will still stay an erratic process, where the most-promising application could still be withdrawn and reintroduced (a couple of times). As discussed in section **6. Discussion and future research**, there are many factors that can hinder the immediate, smooth large-scale diffusion of an application after executing the ten-step framework. Examples are completeness of the list of potential future applications for the breakthrough technology and proper selection of the most appropriate one, to name a few. The level of chaos will therefore most likely never be reduced to zero. However, if all issues surrounding the line of thought and the ten-step framework as discussed in the current work are solved in the future, overleaping the adaptation phase in totality might become a reality.

With the current work, a new, more structured way of thinking about the (pre-FFE phase of the) NPD process is introduced. It surprises me that this way of thinking has not been initiated a long time ago. NPD endeavours are surrounded by so much uncertainty that failure rates of NPD projects are tremendous. The failure of so many NPD projects must have serious detrimental effects on the economic stability of many firms. It buzzes me that the current malfunctioning of the way of thought about the NPD process, as is obvious from the high failure rates, has, to date, not triggered a noteworthy number of researchers and/or businesses to investigate how this inefficient process can be optimised.

The results of this thesis will hopefully spark the interest of the scientific and managerial world to better structure the (pre-FFE phase of the) NPD process.

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Appendices

Appendix 1: seven core actors

To understand why applications are, or are not, adopted by the main public, Ortt and Kamp (2022) investigated which actors are necessary for large-scale diffusion to take off.

In their work, the two researchers examined a socio-technical system, namely a technological innovation system (TIS), applied a systems view, and took a company perspective. Carlsson and Stankiewicz define a technological system as “a network of agents interacting in a specific *economic/industrial area* under a particular *institutional infrastructure* or set of infrastructures and involved in the generation, diffusion, and utilization of technology” (Carlsson & Stankiewicz, 1991, p. 111). A TIS it thus a technological system in innovation and was chosen since it comprises of all (f)actors around a certain technological innovation (Ortt & Kamp, 2022). Derived from the preceding two explanations, a TIS can be expected to be comprised of at least the following structural components: (1) a technology, (2) a demand side, (3) a network of actors, and (4) supporting institutions. Ortt and Kamp focused their research on a subset of technological innovations, being radically new ones. Examples of cases the two researchers looked at are healthcare equipment and medicines, chemical substances or metals, defence and aerospace systems, and mechanical or electronic systems, among others.

The analysis of Ortt and Kamp led to the formation of a list of seven core actors, termed ‘building blocks’, that are crucial for large-scale diffusion to be initiated. If a core actor is incompatible with another core actor, incomplete, or even absent, large-scale diffusion can be seriously hampered. The seven building blocks are listed hereafter together with a concise description.

Product performance and quality. Upon comparison to alternative, competing products, an innovation should now, or in the proximate future, yield at least good performance and quality. Often, innovations suffer from low(er) performance and/or quality. Insufficient performance of quality of an innovation can block its large-scale diffusion.

Product price. Upon comparison to alternative, competing products, an innovation should be available for at least a comparable price. Price is not only defined by absolute buying cost but is also composed of factors like the time needed to familiarise with an innovation and switching costs that arise when customers need to swap a product that they currently use for an innovation. An unreasonable price can obstruct large-scale diffusion.

Production system. Upon comparison to the production system behind alternative, competing products, an innovation should have a production system that can deliver considerable quantities of the innovation at high quality. Taking advantage of economies of scale increases the competitiveness of an innovation but setting up the system can consume a lot of resources. An incomplete production system can hinder the development and diffusion of an innovation.

Complementary products and services. Upon comparison to alternative, competing products, an innovation should have sufficient availability of complementary services or products that are needed for its repair, use, disposal, maintenance, distribution, production, adoption, and development. A lack of complementary products or services can oppose large-scale diffusion.

Network formation and coordination. Upon comparison to the supply chain network of alternative, competing products, an innovation should at least have a comparable network of actors in its supply chain. This network also needs to be coordinated well. A lack of actors or a poorly coordinated network of actors can hamper large-scale diffusion.

Customers. Upon comparison to alternative, competing products, an innovation should have a customer segment. Potential customers should have the willingness and means to obtain and employ an innovation, should be aware of its existence and should realise its potential benefits. A lack of customers can block the development and diffusion of an innovation.

Innovation-specific institutions. Upon comparison to alternative, competing products, an innovation should have a set of regulations, laws, standards, and government policies that is established by innovation-specific institutions. An incomplete legal framework can increase uncertainty for companies and can therefore limit large-scale diffusion.

Knowing the status of the core actors of an innovation is crucial for a company to know if large-scale diffusion is possible and to evaluate whether introducing the innovation on a large scale is a logical option.

Appendix 2: seven influencing factors

If all core actors are compatible and in place, a complete TIS forms, and applications can diffuse on a large scale. However, this large-scale diffusion can be troubled if a building block is incomplete, incompatible with other core actors, or missing.
To understand why a certain core actor is incompatible with another core actor, incomplete, or even missing, Ortt and Kamp came up with an additional list of seven factors that influence complete TIS formation. The seven influencing factors are listed hereafter together with a concise description.

Knowledge and awareness of technology. Applied as well as fundamental technological knowledge is needed. Combining both, companies have knowhow about technical principles of components of the TIS and have the capacity to develop, maintain, repair, and improve components. Lack of technological knowledge can limit complete TIS formation.
Knowledge and awareness of application and market. Companies must know in which application and how an innovation can be used. It also entails knowledge on relevant actors, like customers and suppliers. Lack of application and market insights can hamper complete TIS formation.
Natural, human, and financial resources. Natural (creation of complementary products, production systems, and products), human (knowledge and competences), and financial (monetary) resources need to be gathered. Lack of resources can hamper complete TIS formation.
Competition. Especially in the market adaptation phase, multiple versions of a product or service that implements a breakthrough technology can emerge. Next to this, during the formation of a complete TIS, innovations that that incorporate old technologies compete with the innovation. Competition can block complete TIS formation.
Macro-economic and strategic aspects. Involve the present way of doing business and the market structure. These conditions, like e.g., a recession or economic growth, can obstruct complete TIS formation.
Socio-cultural aspects. Mostly concerns the norms and values of all relevant stakeholders surrounding an innovation. Socio-cultural aspects can be rather informal and can be subject to change over time. A mismatch of socio-cultural aspects between stakeholders can seriously affect complete TIS formation.
Accidents and events. These can happen within a TIS (an accident in the production process) or outside the TIS (a natural disaster or a war). Accidents and events can promote the emergence of radically new technological innovations but can also hamper complete TIS formation.

Knowing the root cause as to why a particular building block is not in place is essential for companies to set up appropriate introduction strategies. Multiple reasons can namely exist for a core actor not to be in place. If, for instance, a customer-base is lacking, this can find its origin in the fact that customers have insufficient knowledge about the technology or because they do not have the financial resources to attain the innovation. If the latter is the case, a company can better focus on a high-end of the market, or introduce a cheap version of the innovation, rather than educating potential customers.

Controversially, it is also important to know *if* a certain influencing factor is limiting large-scale diffusion. It could for instance very well be that knowledge of a technology is lacking but that this lack of knowledge does not affect a core actor and thereby does not hinder large-scale diffusion. In other words, influencing factors only become a barrier to large-scale diffusion if they influence a building block.

Appendix 3: introducing applications

If all core actors are in place and form a complete TIS, a company can choose to bring an application to market via a particular large-scale introduction strategy. Luckily, if a certain core actor is missing, incompatible with other core actors, or incomplete, and a firm knows *why* this is the case, a company can still choose to bring a product or service that implements a breakthrough technology to market. Ortt and Kamp (2022) suggest companies do this via *niche introduction strategies*.
Niche introduction strategies are strategies that focus on a small customer base that has specific, uniform demands and wishes (Dalgic & Leeuw, 1994). Customers in niche markets can have several unique characteristics: (1) they can often afford expensive innovations before the main public can, (2) they have wishes and desires that are (yet) unmatched, (3) they have an innovative mindset and like to experiment with new innovations before the mass market does. Companies can make use of such customers when uncertainty about a technology as well as its market is still present.
By making use of a niche introduction strategy, an application can benefit from the core actors that are in place, whilst working around existing barriers to large-scale diffusion. Ortt et al. (2013) formulated ten niche introduction strategies. Depending on the core actor hampering large-scale diffusion and the influencing factor that causes this, a particular niche introduction strategy can be chosen. A list of ten possible niche introduction strategies is stated next together with a concise description.

Demo, experiment, and develop niche strategy. An insufficient knowledge base on the technology results in a product of relatively poor quality. This niche introduction strategy introduces the product in public but in a controlled manner so that experimenting can be done to develop the product further.
Top niche strategy. A lack of knowledge on the technology, an affected production system, or lacking resources result in a product with an unreasonable price. This niche introduction strategy only fabricates products when they are ordered or only targets high-end customers.
Subsidised niche strategy. A lack of knowledge on the technology, an affected production system, or lacking resources result in a product with an unreasonable price. This niche introduction strategy makes use of subsidies if the use of the product is judged to be societally important or relevant.
Redesign niche strategy. A lack of knowledge on the technology, an affected production system, or lacking resources result in a product with an unreasonable price. Alternatively, knowledge of the application is lacking, or socio-cultural aspects hamper diffusion or limits the number of customers or suppliers. This niche introduction strategy introduces the product in a simpler form and mostly leads to redesign.
Dedicated system or stand-alone niche strategy. Complementary products and services are lacking because of insufficient knowledge about the technology. This niche strategy uses the product in stand-alone mode or complementary products and services are designed.
Hybridisation or adaptor niche strategy. Complementary products and services are lacking because of insufficient knowledge about the technology or limited resources. This niche introduction strategy makes use of the complementary products and services of an old product or uses a convertor or an adaptor to bridge between old complementary products and services and the innovation.
Educate niche strategy. Limited customers or suppliers are available due to lacking knowledge about the technology. This niche introduction strategy educates suppliers or potential customers.

Geographic niche strategy. Accidents or events, socio-cultural or macro-economic aspects, or lacking knowledge of the technology result in an inappropriate legal framework. Alternatively, a lack of resources results in unavailability of the product or its complementary products and services. This niche introduction strategy employs the innovation in a different geographic location where the problems faced are less severe.
Lead user niche strategy. Knowledge of the application is lacking or accidents or events, socio-cultural or macro-economic aspects limit the number of customers or suppliers. This niche introduction strategy looks for co-developers or lead users who like to experiment with the innovation.
Explore multiple markets niche strategy. Knowledge of the application is lacking. This niche introduction strategy explores multiple use cases.

Many niche introduction strategies exist. Companies can choose an appropriate strategy, a combination of strategies, or multiple successive strategies, depending on which core actor is missing and which influencing factor causes this.
A summary of the framework sketched in appendices 1, 2, and 3 is shown in **Figure A.3.1**.

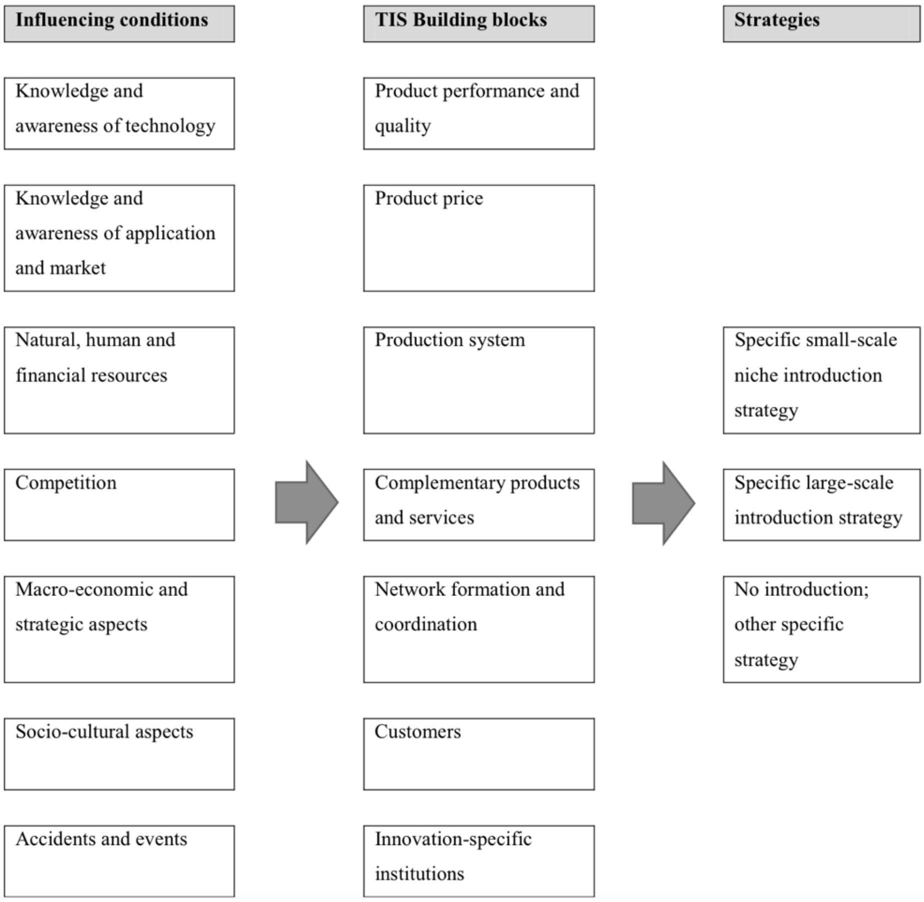

Figure A.3.1. A framework for the formation of a complete TIS in combination with strategies for introducing an application to the market. Reprinted from Ortt and Kamp (2022).

Appendix 4: coding for R

Below the lines of code that can be implemented into R programming software to yield the technology dendrogram are shown. The lines proceeded by a hashtag describe what is done by each step.

```
# Load the required packages
library(cluster)
library(openxlsx)
library(proxy)

# Set the working directory to where the file is stored
setwd("/Users/jessethoen/Desktop/Master thesis MoT/Co-occurence matrix/Basic research/")

# Read in the data from the co-occurrence matrix sheet
co_occurrence_matrix <- read.xlsx("Co-occurrence matrix.xlsx", sheet = "Co-occurrence
matrix", startRow = 1, colNames = FALSE)

# Convert the data so that R recognises it as a matrix
co_occurrence_matrix <- as.matrix(co_occurrence_matrix)

# Calculate the document frequency for each keyword. In other words, how often does a
keyword occur?
doc_freq <- apply(co_occurrence_matrix[-1,-1], 1, function(x) sum(x > 0))

# Calculate the inverse document frequency for each keyword. The IDF downweighs
frequently occurring keywords (which may be not so informative) and upweights less
frequently occurring keywords (which might hold more value). Its formula is: IDF = log(N/df),
where N is the total number of keywords and df shows how often a keyword occurs (as
determined in the previous step). So, this is a normalisation step
idf <- log(nrow(co_occurrence_matrix[-1,-1])/doc_freq)

# Compute the vector representation for each keyword by multiplying the co-occurrence
matrix by the matrix representation of the idf vector (element-wise multiplication) (take note
of the ncol)
numeric_co_occurrence <- matrix(as.numeric(co_occurrence_matrix[-1,-1]), ncol = 2715)
keyword_vectors <- numeric_co_occurrence * diag(idf)

# Calculate the pairwise cosine similarity with the indirect Salton's cosine and form the
distance matrix
distance_matrix <- as.matrix(dist(keyword_vectors), method = function(x) cosine(x, method =
"salton"))

# Cluster the keywords with the Ward method
ward_clusters <- agnes(distance_matrix, method = "ward")

# Plot the dendrogram
plot(ward_clusters, main = "Technology dendrogram")
```

To verify whether the distance matrix generated by the above code is correct, the code up until the generation of the distance matrix was tested on a dummy matrix of ten rows and ten columns. This verification is shown in **Figure A.4.1** on the next page.

```
> # Load the required packages
> library(cluster)
> library(openxlsx)
> library(proxy)
>
> # Set the working directory to where the file is stored
> setwd("/Users/jessethoen/Desktop/Master thesis MoT/Co-occurence matrix/Basic research/")
>
> # Read in the data from the co-occurrence matrix sheet
> co_occurrence_matrix <- read.xlsx("Co-occurrence matrix example.xlsx", sheet = "Sheet1", startRow = 1, colNames = FALSE)
>
> # Convert the data so that R recognises it as a matrix
> co_occurrence_matrix <- as.matrix(co_occurrence_matrix)
>
> print(co_occurrence_matrix[-1,-1])
   X2  X3  X4  X5   X6  X7   X8   X9   X10 X11
2  "5" "2" "0" "1"  "5" "9"  "2"  "8"  "4" "6"
3  "2" "7" "1" "0"  "6" "0"  "8"  "0"  "1" "5"
4  "0" "1" "3" "0"  "4" "8"  "2"  "1"  "0" "0"
5  "1" "0" "0" "4"  "8" "11" "2"  "6"  "3" "1"
6  "5" "6" "4" "8"  "6" "0"  "3"  "1"  "0" "9"
7  "9" "0" "8" "11" "0" "8"  "4"  "7"  "1" "12"
8  "2" "8" "2" "2"  "3" "4"  "4"  "10" "5" "8"
9  "8" "0" "1" "6"  "1" "7"  "10" "9"  "2" "0"
10 "4" "1" "0" "3"  "0" "1"  "5"  "2"  "7" "3"
11 "6" "5" "0" "1"  "9" "12" "8"  "0"  "3" "1"
>
> # Calculate the document frequency for each keyword. In other words, how often does a keyword occur?
> doc_freq <- apply(co_occurrence_matrix[-1,-1], 1, function(x) sum(x > 0))
>
> print(doc_freq)
 2  3  4  5  6  7  8  9 10 11
 9  7  6  8  8  8 10  8  8  8
>
> # Calculate the inverse document frequency for each keyword. The IDF downweighs frequently occurring keywords (which may be not so informative) and upweig
is: IDF = log(N/df), where N is the total number of keywords and df shows how often a keyword occurs (as determined in the previous step). So, this is a non
> idf <- log(nrow(co_occurrence_matrix[-1,-1])/doc_freq)
>
> print(idf)
        2         3         4         5         6         7         8         9        10        11
0.1053605 0.3566749 0.5108256 0.2231436 0.2231436 0.2231436 0.0000000 0.2231436 0.2231436 0.2231436
>
> # Compute the vector representation for each keyword by multiplying the co-occurrence matrix by the matrix representation of the idf vector (element-wise 
> numeric_co_occurrence <- matrix(as.numeric(co_occurrence_matrix[-1,-1]), ncol = 10)
>
> print(numeric_co_occurrence)
      [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10]
 [1,]    5    2    0    1    5    9    2    8    4     6
 [2,]    2    7    1    0    6    0    8    0    1     5
 [3,]    0    1    3    0    4    8    2    1    0     0
 [4,]    1    0    0    4    8   11    2    6    3     1
 [5,]    5    6    4    8    6    0    3    1    0     9
 [6,]    9    0    8   11    0    8    4    7    1    12
 [7,]    2    8    2    2    3    4    4   10    5     8
 [8,]    8    0    1    6    1    7   10    9    2     0
 [9,]    4    1    0    3    0    1    5    2    7     3
[10,]    6    5    0    1    9   12    8    0    3     1
> print(diag(idf))
           [,1]      [,2]      [,3]      [,4]      [,5]      [,6] [,7]      [,8]      [,9]     [,10]
 [1,] 0.1053605 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000    0 0.0000000 0.0000000 0.0000000
 [2,] 0.0000000 0.3566749 0.0000000 0.0000000 0.0000000 0.0000000    0 0.0000000 0.0000000 0.0000000
 [3,] 0.0000000 0.0000000 0.5108256 0.0000000 0.0000000 0.0000000    0 0.0000000 0.0000000 0.0000000
 [4,] 0.0000000 0.0000000 0.0000000 0.2231436 0.0000000 0.0000000    0 0.0000000 0.0000000 0.0000000
 [5,] 0.0000000 0.0000000 0.0000000 0.0000000 0.2231436 0.0000000    0 0.0000000 0.0000000 0.0000000
 [6,] 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.2231436    0 0.0000000 0.0000000 0.0000000
 [7,] 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000    0 0.0000000 0.0000000 0.0000000
 [8,] 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000    0 0.2231436 0.0000000 0.0000000
 [9,] 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000    0 0.0000000 0.2231436 0.0000000
[10,] 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000    0 0.0000000 0.0000000 0.2231436
>
> keyword_vectors <- numeric_co_occurrence * diag(idf)
>
> print(keyword_vectors)
           [,1]     [,2]     [,3]      [,4]     [,5]     [,6] [,7]     [,8]     [,9]     [,10]
 [1,] 0.5268026 0.000000 0.000000 0.0000000 0.000000 0.000000    0 0.000000 0.000000 0.0000000
 [2,] 0.0000000 2.496725 0.000000 0.0000000 0.000000 0.000000    0 0.000000 0.000000 0.0000000
 [3,] 0.0000000 0.000000 1.532477 0.0000000 0.000000 0.000000    0 0.000000 0.000000 0.0000000
 [4,] 0.0000000 0.000000 0.000000 0.8925742 0.000000 0.000000    0 0.000000 0.000000 0.0000000
 [5,] 0.0000000 0.000000 0.000000 0.0000000 1.338861 0.000000    0 0.000000 0.000000 0.0000000
 [6,] 0.0000000 0.000000 0.000000 0.0000000 0.000000 1.785148    0 0.000000 0.000000 0.0000000
 [7,] 0.0000000 0.000000 0.000000 0.0000000 0.000000 0.000000    0 0.000000 0.000000 0.0000000
 [8,] 0.0000000 0.000000 0.000000 0.0000000 0.000000 0.000000    0 2.008292 0.000000 0.0000000
 [9,] 0.0000000 0.000000 0.000000 0.0000000 0.000000 0.000000    0 0.000000 1.562005 0.0000000
[10,] 0.0000000 0.000000 0.000000 0.0000000 0.000000 0.000000    0 0.000000 0.000000 0.2231436
>
> # Calculate the pairwise cosine similarity with the indirect Salton's cosine and form the distance matrix
> distance_matrix <- as.matrix(dist(keyword_vectors), method = function(x) cosine(x, method = "salton"))
>
> print(distance_matrix)
           1        2        3         4        5        6         7        8        9        10
1  0.0000000 2.551696 1.620496 1.0364409 1.438774 1.861257 0.5268026 2.076236 1.648448 0.5721136
2  2.5516964 0.000000 2.929525 2.6514755 2.833052 3.069265 2.4967246 3.204196 2.945079 2.5066764
3  1.6204957 2.929525 0.000000 1.7734639 2.034953 2.352709 1.5324769 2.526207 2.188229 1.5486376
4  1.0364409 2.651476 1.773464 0.0000000 1.609111 1.995857 0.8925742 2.197709 1.799041 0.9200444
5  1.4387740 2.833052 2.034953 1.6091110 0.000000 2.231436 1.3388613 2.413667 2.057282 1.3573292
6  1.8612565 3.069265 2.352709 1.9958566 2.231436 0.000000 1.7851484 2.687004 2.372048 1.7990408
7  0.5268026 2.496725 1.532477 0.8925742 1.338861 1.785148 0.0000000 2.008292 1.562005 0.2231436
8  2.0762364 3.204196 2.526207 2.1977091 2.413667 2.687004 2.0082920 0.000000 2.544228 2.0206508
9  1.6484478 2.945079 2.188229 1.7990408 2.057282 2.372048 1.5620049 2.544228 0.000000 1.5778632
10 0.5721136 2.506676 1.548638 0.9200444 1.357329 1.799041 0.2231436 2.020651 1.577863 0.0000000
```

Figure A.4.1. Screenshot of the coding used to generate the distance matrices, tested on a dummy matrix of ten rows and ten columns. The output of each step is printed.

To cluster the branches of the technology dendrogram into eighteen clusters, the code provided below can be implemented into R programming software. The lines proceeded by a hashtag describe what is done by each step.

```
# Load the required packages
library(cluster)
library(openxlsx)
library(proxy)
library(dendextend)

# Set the working directory to where the file is stored
setwd("/Users/jessethoen/Desktop/Master thesis MoT/Co-occurence matrix/Basic research/")

# Read in the data from the co-occurrence matrix sheet
co_occurrence_matrix <- read.xlsx("Co-occurrence matrix.xlsx", sheet = "Co-occurrence
matrix", startRow = 1, colNames = FALSE)

# Convert the data so that R recognises it as a matrix
co_occurrence_matrix <- as.matrix(co_occurrence_matrix)

# Calculate the document frequency for each keyword. In other words, how often does a
keyword occur?
doc_freq <- apply(co_occurrence_matrix[-1,-1], 1, function(x) sum(x > 0))

# Calculate the inverse document frequency for each keyword. The IDF downweighs
frequently occurring keywords (which may be not so informative) and upweights less
frequently occurring keywords (which might hold more value). Its formula is: IDF = log(N/df),
where N is the total number of keywords and df shows how often a keyword occurs (as
determined in the previous step). So, this is a normalisation step
idf <- log(nrow(co_occurrence_matrix[-1,-1])/doc_freq)

# Compute the vector representation for each keyword by multiplying the co-occurrence
matrix by the matrix representation of the idf vector (element-wise multiplication) (take note
of the ncol)
numeric_co_occurrence <- matrix(as.numeric(co_occurrence_matrix[-1,-1]), ncol = 2715)
keyword_vectors <- numeric_co_occurrence * diag(idf)

# Calculate the pairwise cosine similarity with the indirect Salton's cosine and form the
distance matrix
distance_matrix <- as.matrix(dist(keyword_vectors), method = function(x) cosine(x, method =
"salton"))

# Cluster the keywords with Ward method
ward_clusters <- agnes(distance_matrix, method = "ward")

# Cut the dendrogram at a height of 10,000 (adjust as seems appropriate)
clusters <- cutree(ward_clusters, h = 10000)

# Generate a set of colours equal to the number of clusters
num_clusters <- length(unique(clusters))

# Colour the clusters of the dendrogram
dend <- as.dendrogram(ward_clusters)
coloured_dend <- color_branches(dend, k=num_clusters)
```

```
# Plot the dendrogram with coloured branches
plot(coloured_dend, main = "Technology dendrogram")

# Print the keywords that are stored within in each cluster
for (i in unique(clusters)) {
cat("Cluster", i, ": ", paste(row.names(co_occurrence_matrix)[which(clusters == i)], collapse =
", "), "\n")
}
```
